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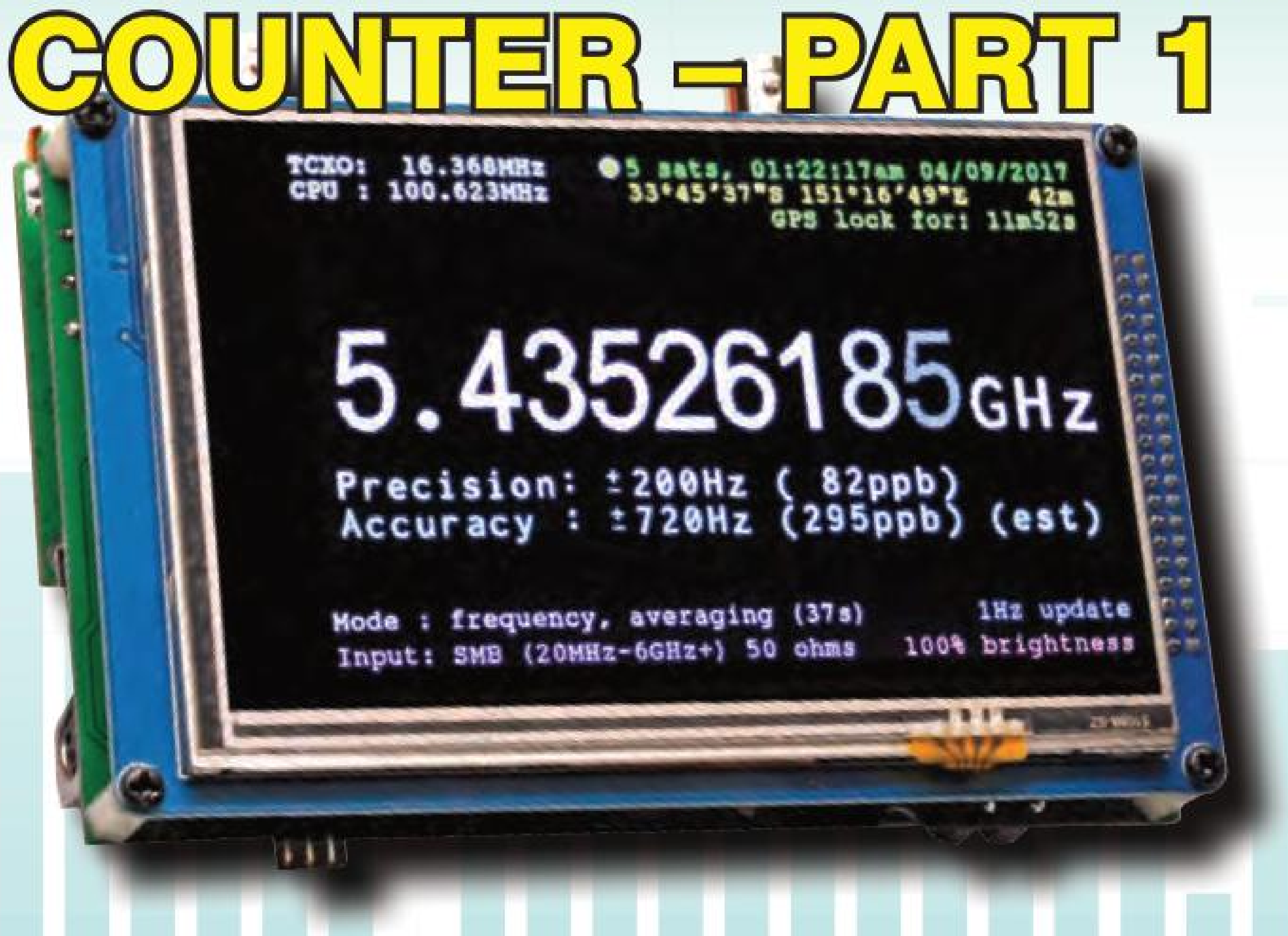
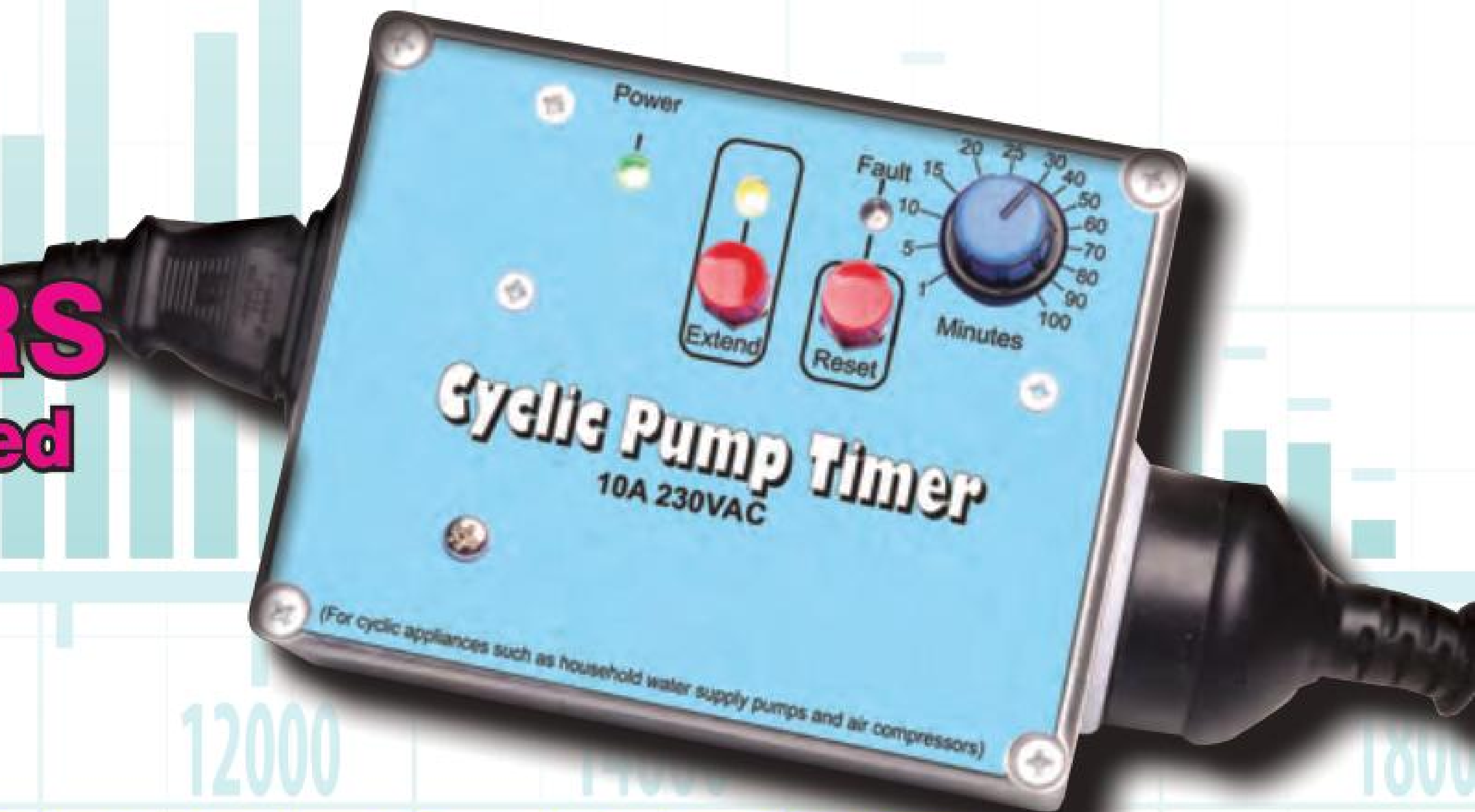
- GPS calibration option



```
TCXO:  16.368MHz        5 sats, 01:22:17am 04/09/2017
CPU : 100.623MHz        33°45'37"S 151°16'49"E    42m
                                GPS lock for: 11m52s

5.43526185GHz

Precision: ±200Hz ( 82ppb)
Accuracy : ±720Hz (295ppb) (est)

Mode : frequency, averaging (37s)          1Hz update
Input: SMB (20MHz-6GHz+) 50 ohms       100% brightness
```

TWO 230V AC MAINS TIMERS

A pair of very handy, power-saving mains-rated timer switches


Power
Fault
Extend
Reset
Minutes
5
10
15
20
25
30
40
50
60
70
80
90
100
Cyclic Pump Timer
10A 230VAC
(For cyclic appliances such as household water supply pumps and air compressors)

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CONSTRUCTING AND HOUSING THIS HI-FI-QUALITY DESIGN

2/3-Way Adjustable Active Crossover
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WIN A MICROCHIP SAMA5D27 Xplained Ultra Board

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Learn to interface these fascinating and useful devices

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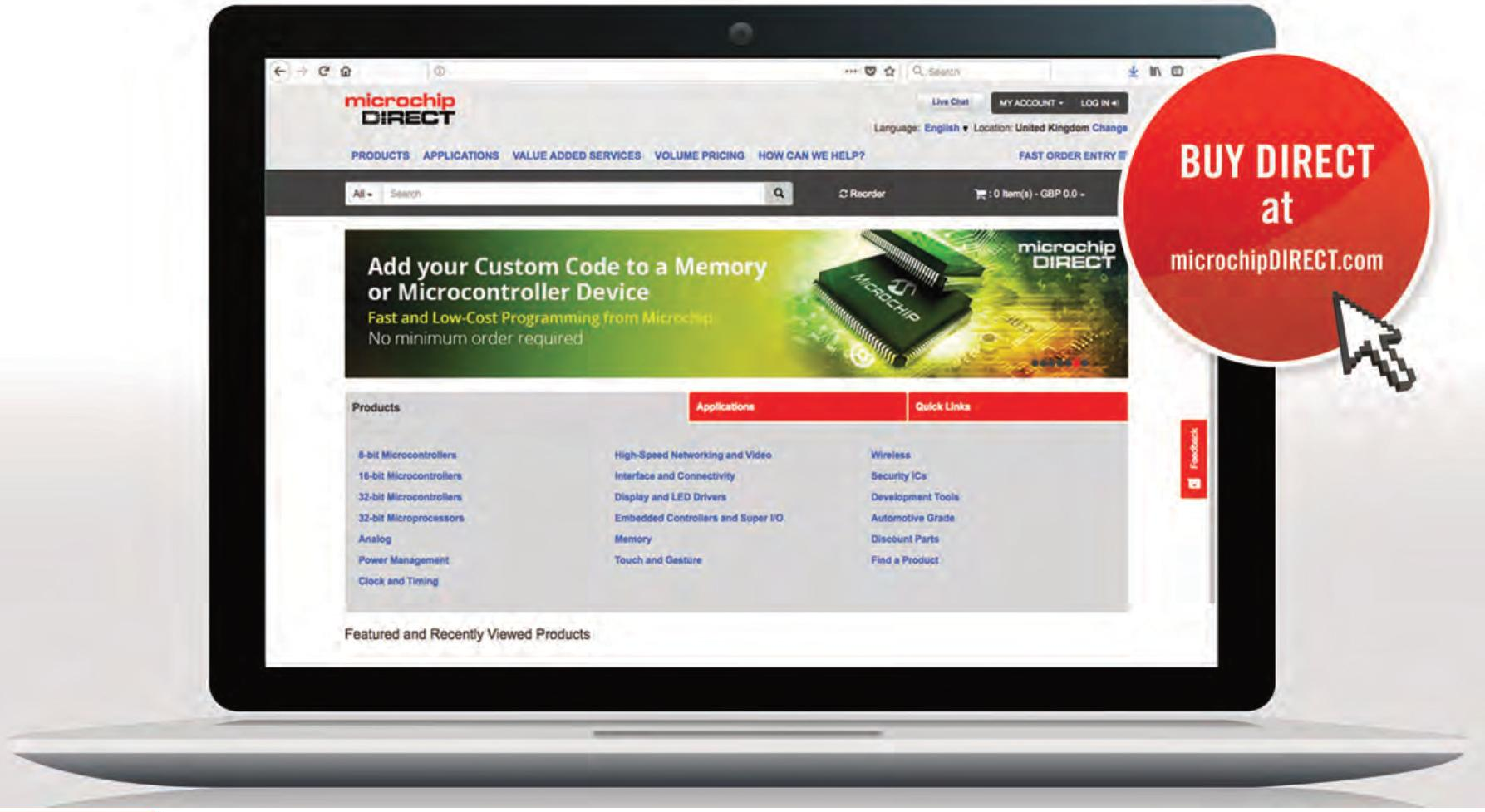

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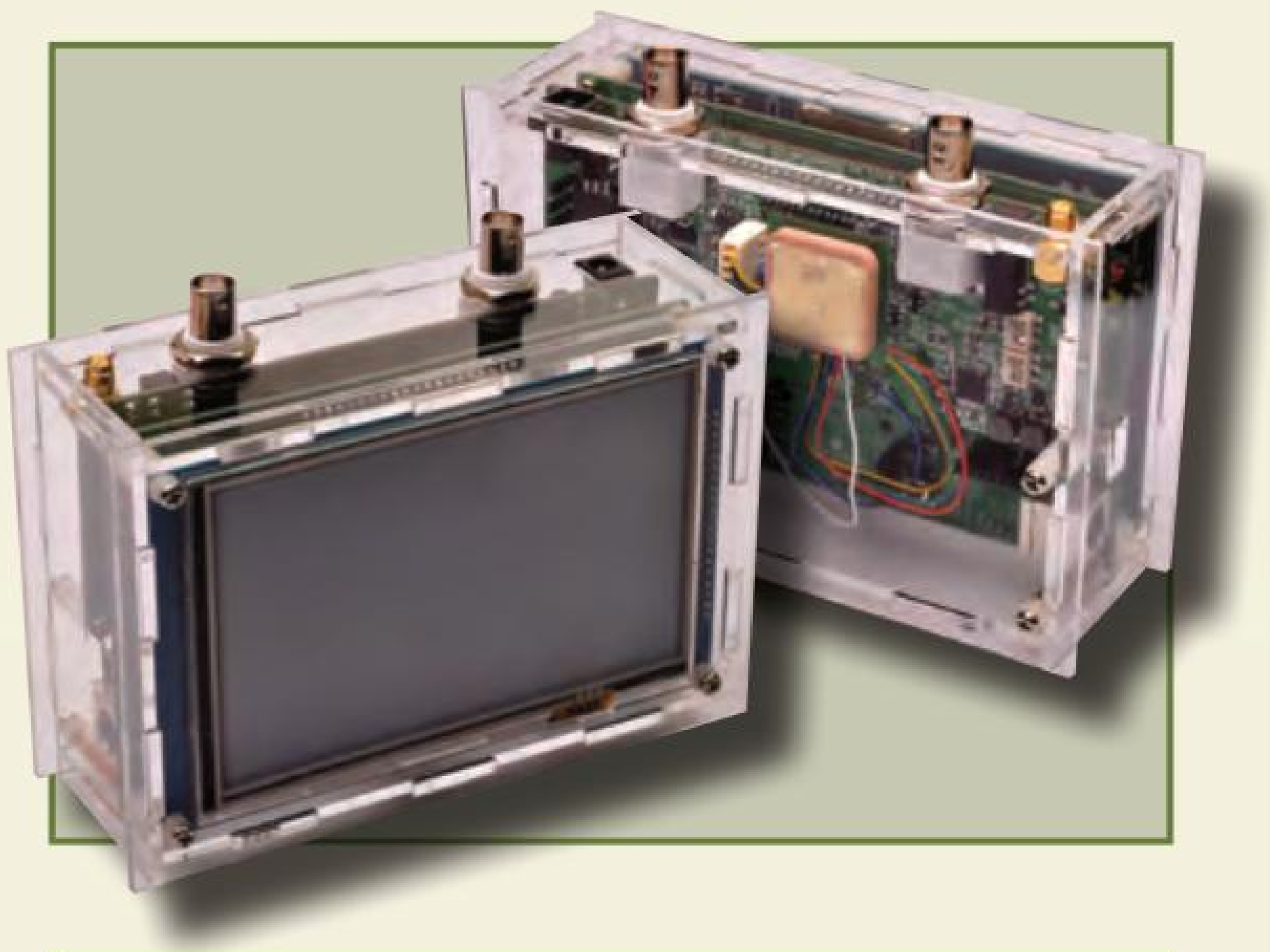

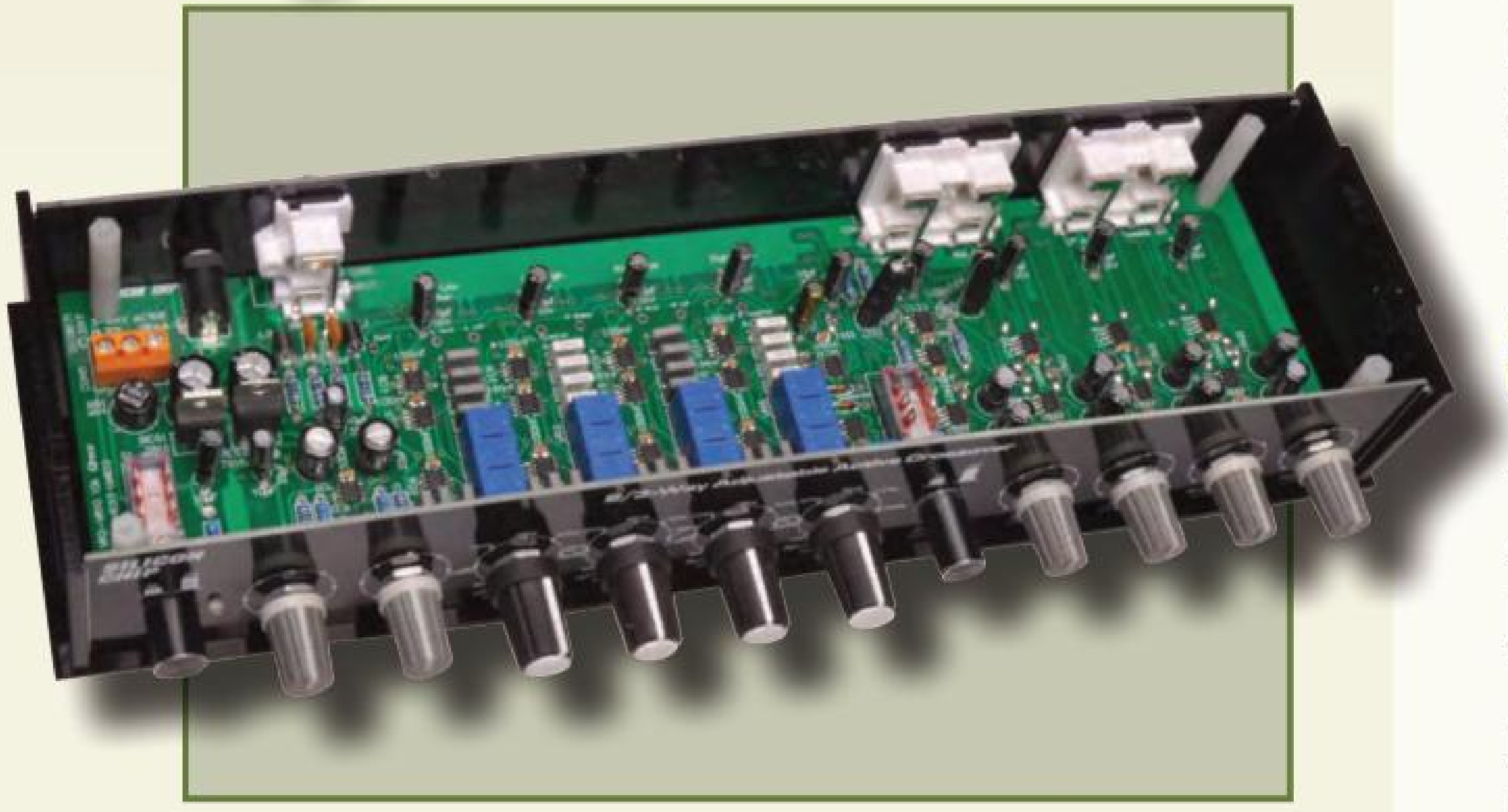

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10A 230VAC
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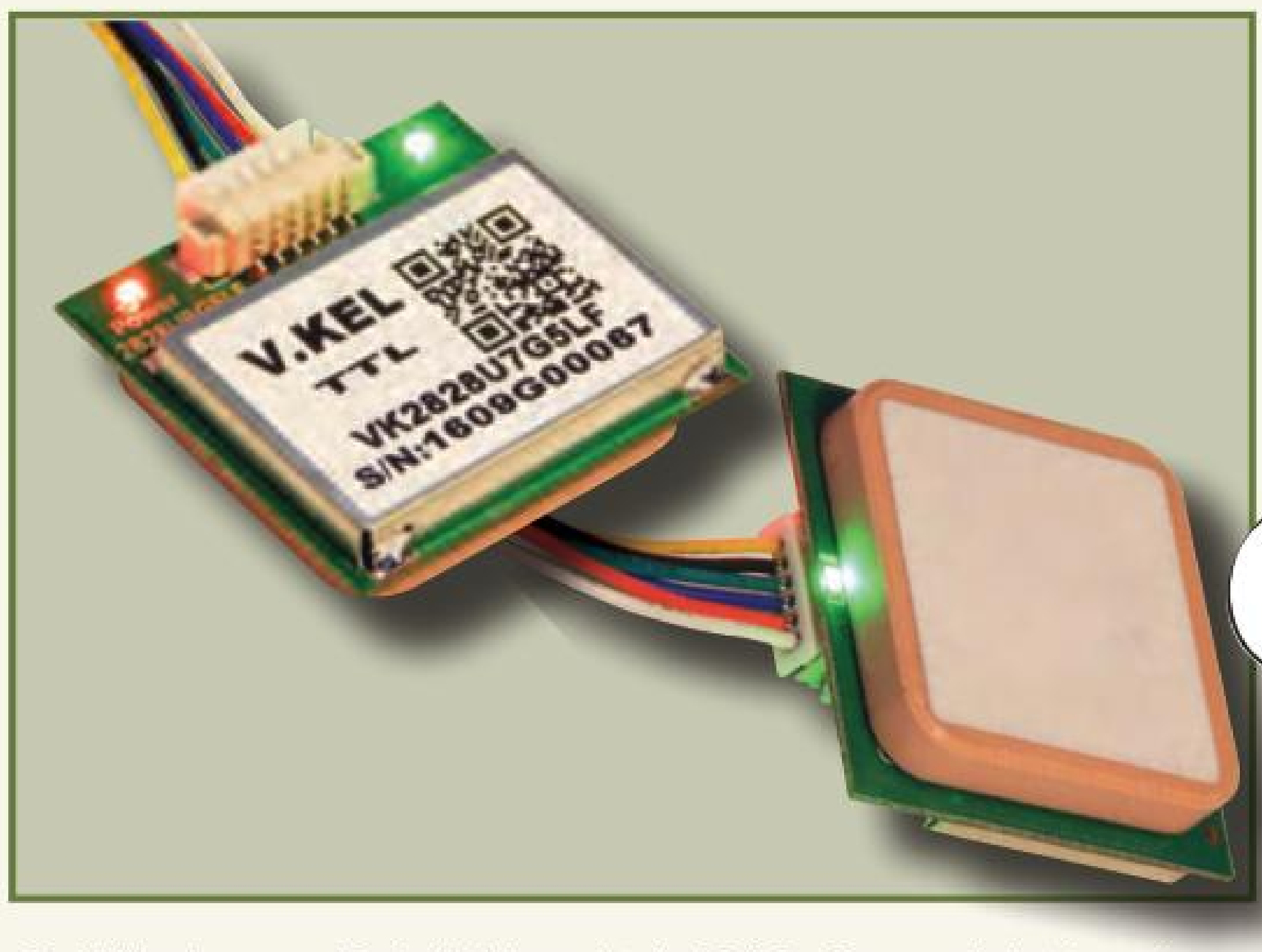

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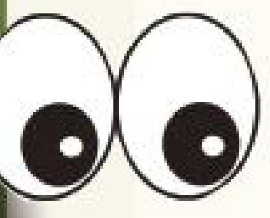

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Assembled with ZIF socket Order Code: AS3149EZIF - ~~£74.96~~ £49.95

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Assembled Order Code: VM110N - £35.94

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*Kit Order Code: 8157KT - **£44.95***
*Assembled Order Code: AS8157 - **£49.96***

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Kit Order Code: 3145KT - ~~£19.95~~ £16.97
Assembled Order Code: AS3145 - £22.97
*Additional DS18S20 Sensors - **£4.96 each***

8-Channel Ethernet Relay Card Module

Connect to your router with standard network cable. Operate the 8 relays or check the status of input from anywhere in world. Use almost any internet browser, even mobile devices. Email status reports, programmable timers... Test software & DLL online.
Assembled Order Code: VM201 - £130.80

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*Kit Order Code: 3179KT - **£15.26***
*Assembled Order Code: AS3179 - **£22.26***

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*Kit Order Code: 3166KT - **£19.96***
*Assembled Order Code: AS3166 - **£25.96***

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*Assembled Order Code: AS3108 - **£89.95***

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The MPLAB PICkit 4 programs faster than its predecessor, using a powerful 32-bit 300MHz SAME70 MCU, and comes ready to support PIC and dsPIC MCU devices. Along with a wider target voltage, the PICkit 4 supports advanced interfaces such as 4-wire JTAG and Serial Wire Debug with streaming Data Gateway, while being backward compatible for demo boards, headers and target systems using 2-wire JTAG and ICSP. The PICkit 4 also has a unique programmer-to-go function with the addition of a micro SD card slot to hold project code and the ability to be powered by the target board.

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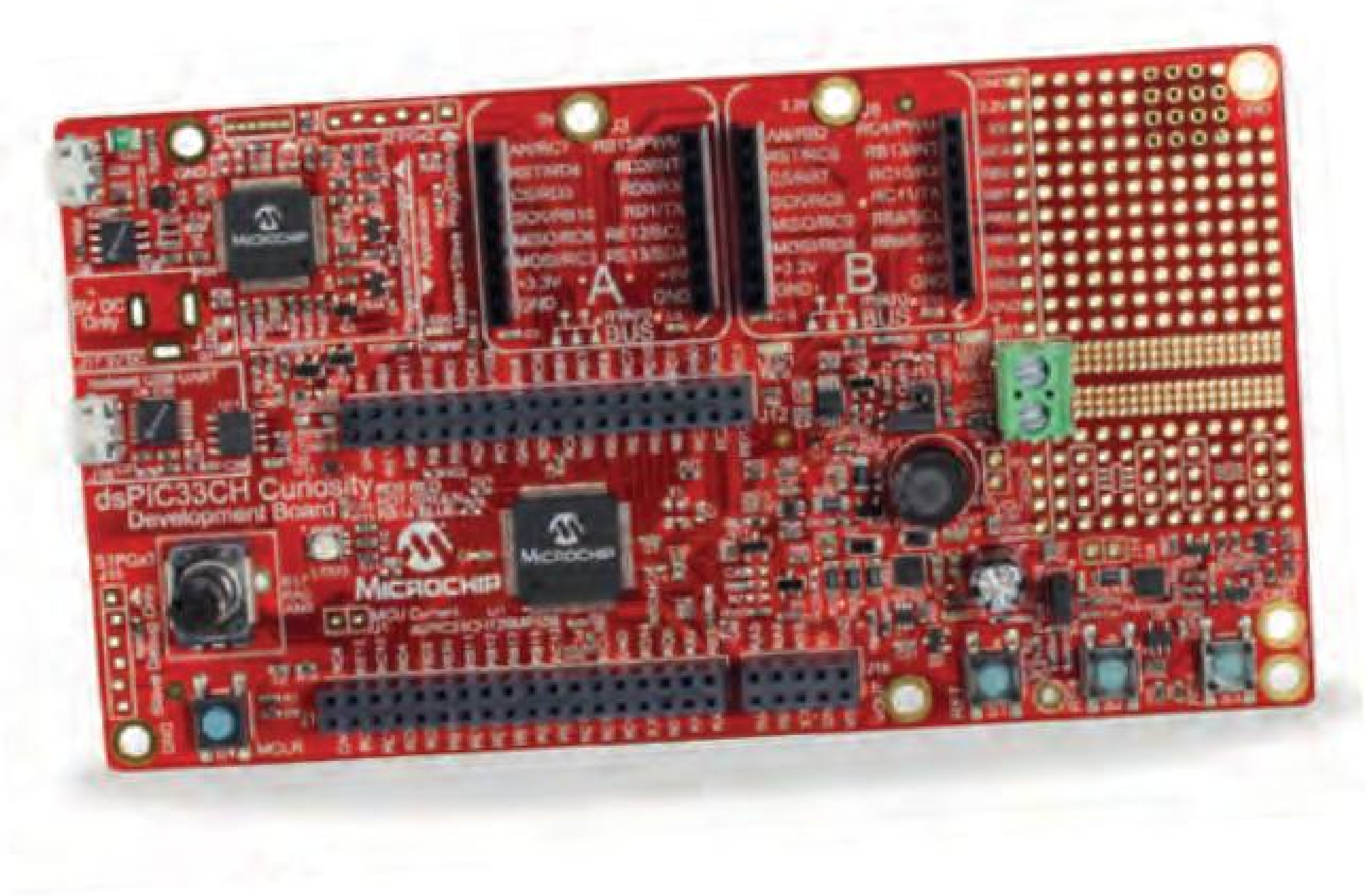
Development Tool of the Month!

dsPIC33CH Curiosity Development Board



Part Number
DM330028

Overview:

The dsPIC33CH Curiosity Development Board (DM330028) is intended as a cost effective development and demonstration platform for the dsPIC33CH128MP508 family of dual core high performance digital signal controllers.

Designed from the ground-up to take full advantage of Microchip's MPLAB® X IDE and MPLAB Xpress Cloud-based IDE, the board includes an integrated programmer/debugger and requires no additional hardware, making it a perfect starting point to explore the dsPIC33CH dual core family.

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VOL. 47 No. 10 OCTOBER 2018

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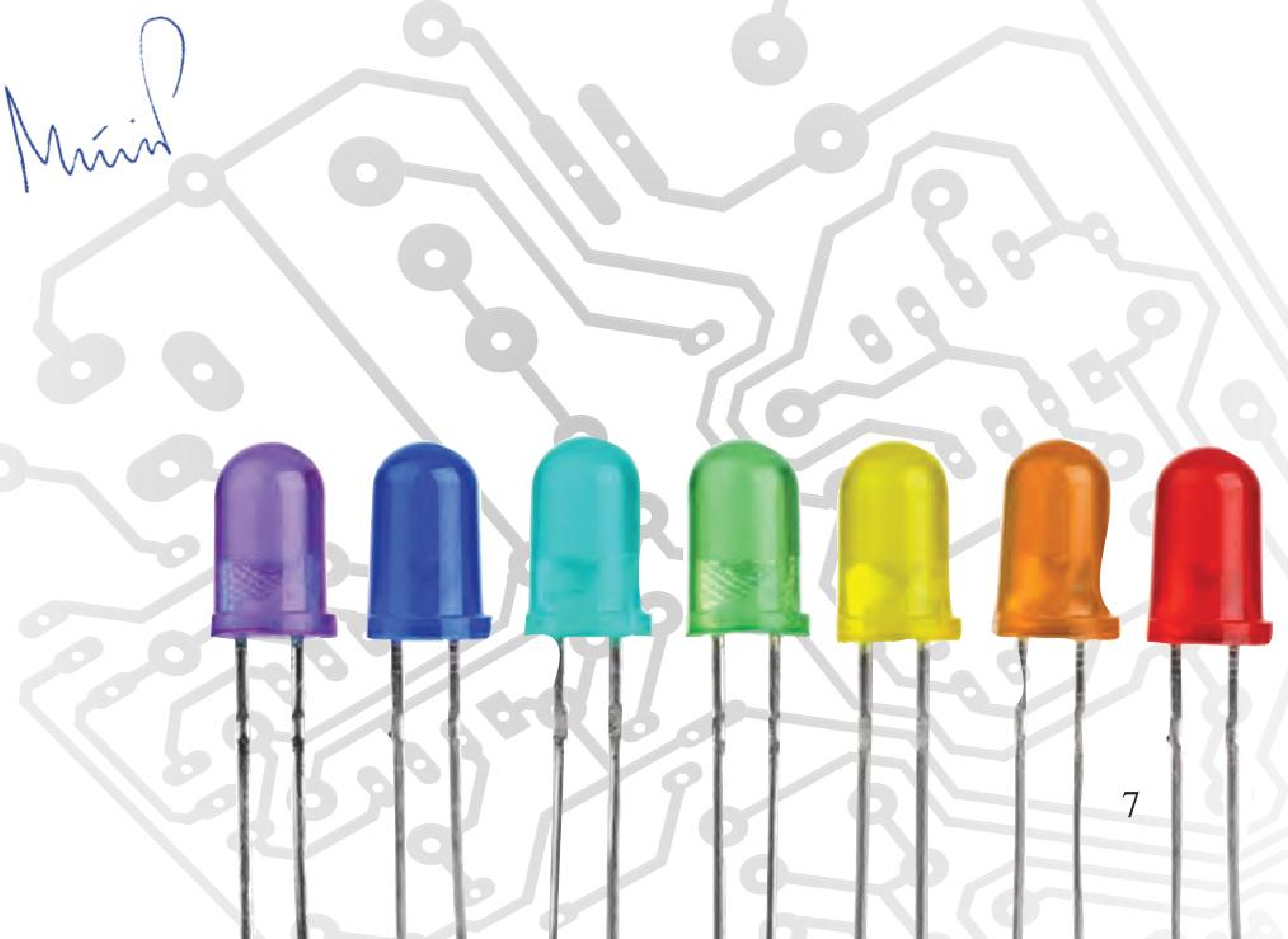
Hunting for parts

This month, we start an exciting project – the *6GHz+ Touchscreen Frequency & Period Counter*. It's a great design for many reasons, not least because you end up with a very useful and flexible piece of test gear. On top of that, it's an impressive piece of high-speed electronics and you get to use the latest and most powerful incarnation of the Micromite. If you're in the market for a meter to measure high frequencies then this is undoubtedly one to seriously consider.

The *6GHz+ Frequency/Counter* neatly brings me to an important topic – finding the right parts for your projects. Nowadays, Google really is your best of best friends when it comes to tracing obscure or hard-to-find parts, but we know it can be a slog. Plus, with the rise of SMD components and their myriad packaging options it can be truly confusing knowing if you really have exactly the right device. When it comes to high-spec circuits like the *6GHz+ Frequency/Counter* you can't play fast and loose with device selection – you really do need to use the components specified. But – and it's a big 'but' – some parts are very difficult to find. This is why, in the parts list, we often quote a distributor part number – for example, those from Digi-Key. The important point here is that the Digi-Key website will tell you the exact manufacturer's code for a device and then you can do a search for that code across all you favourite suppliers – Farnell, Mouser, RS, or your pal round the corner. (On top of the obvious regulars, it's also worth remembering that Amazon, eBay, Banggood and AliExpress are worthy allies in the great hunt for tricky parts.)

That approach will get you everything you need most of the time, but there are some components that are particularly problematic, or simply must come from our partner magazine – *Silicon Chip* in Australia, with which we share a large proportion of the main projects. PCBs and bespoke housing parts are the most obvious examples, but sometimes – as with the *6GHz+ Frequency/Counter* – *Silicon Chip* sells particularly hard-to-to-find parts that are vital in building a project. There is nothing to stop you buying direct from *Silicon Chip*, but it can be inconvenient.

For a long time, the *EPE* shop has offered *Silicon Chip* PCBs, but now we have decided to expand the range so that you'll be able to buy many more *Silicon Chip* items through *EPE*. We won't offer the full *Silicon Chip* range, but we will focus on the items that we think will most help UK-based constructors. We are still working through the process to make this happen and will provide more details next month.



NEWS

A roundup of the latest Everyday News
from the world of
electronics

Patently ingenious: a hunt around recent filings – report *by Barry Fox*

With ‘no comment’, or ‘we’ll get back to you’ now the standard response from most large companies to most tech press questions, patents continue to entertain as a legitimate source of insider information.

Voice and gesture control

Unfortunately, most patents are padded out with largely redundant verbiage, and indexed under obscure titles, to deter snoopers. But US 20180018965 from the Bose Corporation in Framingham, Maryland in the US is a welcome exception: short and to the point, with the helpful title *Combining Gesture and Voice User Interfaces* (see: **http://bit.ly/2mFq9WF**).

Noting that voice control relies on ‘wake up’ words like ‘Alexa’, which the system must hear before acting on a spoken command, which isn’t easy when a speaker is playing music loud, and raises concerns over privacy, Bose suggests combining voice and gesture control. So the music volume is reduced or muted when a gesture command, such as sharp up or down hand motion is detected. The user can then speak a command or use a wakeup word, without the need to shout. The motion detector can be a camera in the room or accelerometer mounted on headphones.

With this approach there would be no need for voice control systems to be continually listening to everything we say.

DAC improvements

Electronics buffs may like to get their teeth into a recent patent filing from Bob Stuart, who developed and promotes the MQA (Master Quality Authenticated) online audio delivery system. The US filing (US 20180167081 – see *Digital To Analogue Conversion*: **http://bit.ly/2OdEhD4**) reveals that Bob Stuart has also been working on overall improvements to digital-to-analogue conversion, applicable to any DAC, and any encoding format, not just those used for MQA.

It’s known that, ‘the signal-to-noise ratio (of DACs) can be improved by up to 3dB by using two identically-driven DACs whose outputs are summed in the analogue domain’, the patent says, ‘However… there remains a need for improved digital-to-analogue converter devices.’

MQA’s new trick is to combine the analogue outputs of multiple DAC devices, all working with the same digital signal but with that signal variously delayed by periods shorter than the sampling frequency. This ‘is beneficial in effectively increasing the number of reconstruction points from which the analogue signal is reconstructed’, says the patent. ‘Moreover, the data signal fed to half of the converters has an inverse relationship with the data signal fed to the other half of the converters, and their analogue outputs are subtracted, whereby analogue non-linear distortion may be reduced by cancellation.’

One of the best ways of doing this, says the patent, is to delay half of the DACs by half the sample period of the incoming signal relative to the other half of the DACs, which doubles the number of reconstruction points; or all DACs may work with different delays. A shaped dither signal of two LSBs (least-significant bits) can also be added.

The system is well-suited to high-quality pulse-code modulated (PCM) signals, says the patent, as the ‘noise or signal distortion often associated with digital-to-analogue conversion may be significantly mitigated’.

Catching the sound of sports field action

Since Ray Dolby died and Dolby Labs was sold off to investors, the company has become very secretive. So patents have become one of the main ways to know what its engineers are thinking and doing.

The title for Dolby’s recently published US patent application 20180139535 – *Action Sound Capture Using Subsurface Microphones* – neatly describes what’s in the tin. A large number of microphones are buried under a football pitch or sports track to pick up the sound of ball strikes or local action. The inevitably muffled sound from the buried microphones is then used to control the pickup of higher quality sound from microphones arranged in free air around the pitch (see: **http://bit.ly/2OdiThb**).

‘In sports broadcasting, action sound (ball strikes and other sounds by sporting event participants) is the most sought-after feature,’ says the patent, ‘yet often the most difficult to capture, due to the high level of unwanted sounds (crowd noise) and the unfeasibility of using close-miking.’

Current practice, says the patent, is to have around twelve directional microphones around the edges of the field, with their output signals manually mixed by an engineer who tries to apply the largest gain to the microphone closest to the action, or pointing at it. But this means ‘stress for the mixing engineer who must follow the action manually with fingers on faders of a console (and) lack of scalability, in the sense that

Patently ingenious: a hunt around recent filings – *continued*

A recent Dolby patent explains buried-microphone technology designed to optimise the capture of on-pitch sounds such as kicking or hitting a ball.

adding more microphones is unfeasible (too complex to mix).'

According to the new scheme, up to a hundred microphones are buried under the grass of a football field, or under the length of a bobsled track, to detect overhead sound and generate location metadata. This data is then used to automatically control the mix of audio from conventional microphones fixed around the track or pitch. Sound from the subsurface microphones can also be mixed in, with frequency equalisation to compensate for the loss of high frequencies caused by burying.

All this can happen far faster than with a human mixing engineer, and with far more microphones than any human engineer could handle.

Light-bulb 'moment'

A world record 117 years of illumination

We've got so used to the idea of replacing a traditional filament light-bulb after a year or two that it's hard to imagine them lasting significantly longer – but it doesn't have to be that way. A long-lasting bulb in a Livermore, California fire station has become a local landmark and point of pride. The bulb is dimmer than in its youth – the 60W hand-blown bulb with a carbon filament made by the Shelby Electric Company now only manages a soft 4W. However, its longevity is not just impressive, but a world record of 117 years. More details and even a 'bulb-cam' at: **www.centennialbulb.org**

Drone endurance record

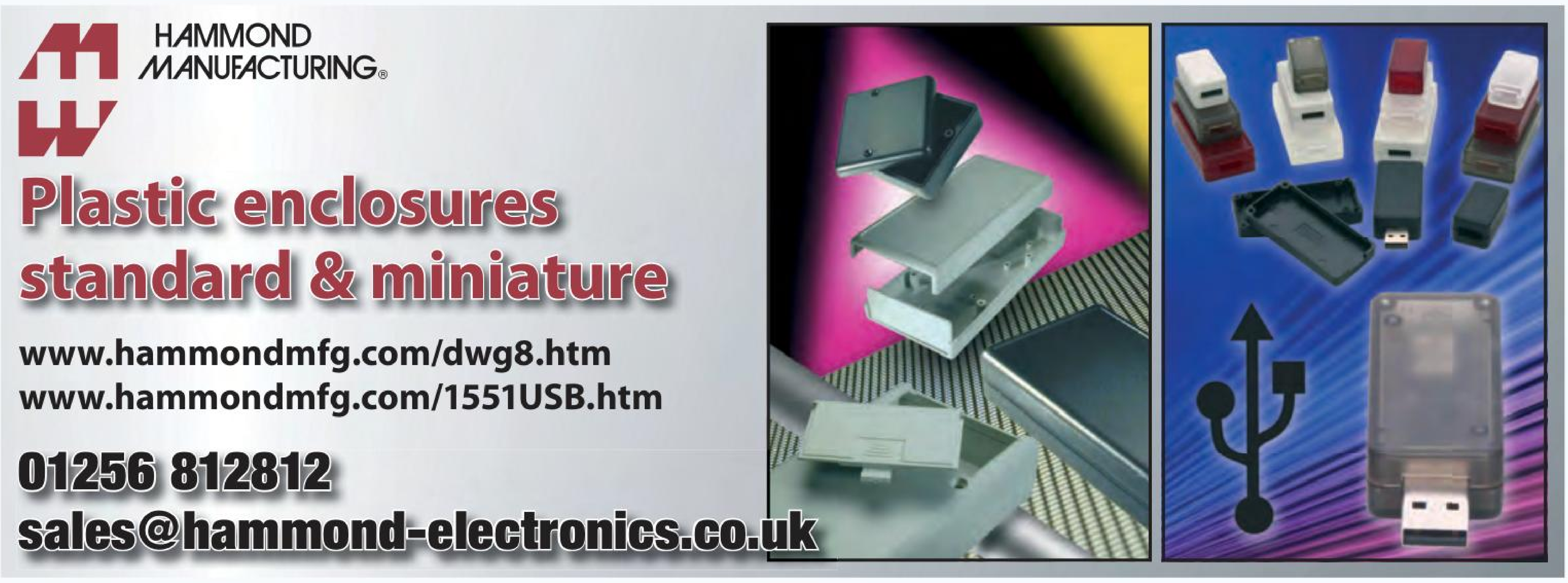
Zephyr S, a British-designed and built solar-powered aircraft has set a new flight-endurance record for a drone, of 25 days, 23 hours and 57 minutes. The purpose of the flight was to demonstrate that unmanned solar-powered aircraft of this sort could compete with satellites for observation and telecomms.

The high-altitude pseudo-satellite (HAPS) was originally developed by British defence company QinetiQ. In 2013 QinetiQ sold the Zephyr programme to Airbus, which has now built a factory in Farnborough.

The drone is capable of providing a continuous autonomous wide-area presence at a fraction of the cost of a satellite. Running exclusively on solar power (no fuel required), it flies at about 65,000 feet, high above the weather and other air traffic.

The Zephyr S has a wingspan of 25m and weighs under 75kg. It is designed to carry payloads that offer HD optical and infrared video, narrowband mobile comms and 100Mbps broadcasting capability. Airbus claim that its cameras offer 15cm resolution at 60,000 feet.

It will soon be joined by a bigger, more advanced version, the Zephyr model T. This upgrade will have a wingspan in excess of 32m, weigh 140kg and offer radar, lidar and broadband comms.



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This series of articles provides a broad-based introduction to choosing and using a wide range of test gear, how to get the best out of each item and the pitfalls to avoid. It provides hints and tips on using, and – just as importantly – interpreting the results that you get. The series deals with familiar test gear as well as equipment designed for more specialised applications.

The articles have been designed to have the broadest possible appeal and are applicable to all branches of electronics. The series crosses the boundaries of analogue and digital electronics with applications that span the full range of electronics – from a single-stage transistor amplifier to the most sophisticated microcontroller system. There really is something for everyone!

Each part includes a simple but useful practical test gear project that will build into a handy gadget that will either extend the features, ranges and usability of an existing item of test equipment or that will serve as a stand-alone instrument. We've kept the cost of these projects as low as possible, and most of them can be built for less than £10 (including components, enclosure and circuit board).

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Are light bulbs ruining your radio?

TechnoTalk

Mark Nelson

As a responsible eco warrior, you did your bit by buying LED lamp bulbs to save the planet – but now they are degrading your radio reception. Maybe you were unaware of the problem, or simply put this down to living in a lousy reception area. Time to wise up!

THE FOLLOWING IS JUST A SMALL selection of comments found on the Internet relating to LED lamp bulbs.

'When the LED spots are on, our FM kitchen radio gets a hiss over the speech (to the extent that BBC R4, our usual channel, is almost unusable)'

'Many LED bulbs are absolutely dreadful on ALL radio bands. It's appalling.'

'I have two LED bulbs. The problem I have is when they are switched on and I stand near them, there's a high-pitched whistle in my digital hearing aids.'

'There is little scope to make radio receivers less sensitive to this type of interference. The problem is that the lights are radiating energy at the frequency being received. Removing the interfering signal is rather like trying to remove the milk from a white coffee – possible but difficult and rather expensive.'

So, you spend a small fortune replacing all your bulbs with environment-friendly LED lamps and then they stab you in the back by degrading or wiping out your radio reception. That's the bad news. The good news is that it doesn't have to be like this. So what's going on?

Inside information

First, a little reminder – as every electronicist knows, LEDs run on low-voltage direct current and cannot be connected directly to a 230V AC supply. However, you can convert 230V AC to low-voltage DC with around 95% efficiency using a switching regulator. Unfortunately, poorly or cheaply designed regulator circuitry can emit wide-spectrum electromagnetic RF noise because of harmonics arising from unsuppressed, fast-switching signal edges. The interference or hash unleashed extends well into the frequency ranges used for FM and DAB radio transmissions. It is discouraging to know that in Germany the government minister responsible for broadcasting talks down the problem, stating that most future radio listening will take place over cable or satellite links, which use more robust digital signals.

Fortunately, there are plenty of well-designed LED bulbs on the market that cause no problems at all; nevertheless, a significant proportion of lamps do generate hash of the worst kind. As long as wholesalers (and end users) buy the cheapest products, the problem can only get worse. There is no effective method of preventing non-compliant products going on sale or even outlawing them. Another electronics magazine recently dismantled a selection of LED lamps and found that the PCBs in some of them were drilled to take suppression components, but they had simply had not been fitted.

The problem is worse with LED bulbs intended to run from 12V supplies, as the website **www.radioandtvhelp.co.uk** explains. These bulbs are typically used as spotlights in kitchens, often as replacements for 12V halogen lamps but without replacing the 'electronic transformers'. LED bulbs present a different kind of load to the power supply, so the original (halogen-expecting) power supply is forced to work outside its operating parameters, causing widespread electrical impulse interference. The only sure remedy is replacing the PSU.

Consumer protection

For the most part there is no problem with branded LED bulbs made in the EU, which should carry the CE mark and be labelled as EMC compliant. The majority of complaints concern cheap LED bulbs, mostly made in China, which do not meet standards for radio frequency interference (RFI). It doesn't help that some DAB radios do not conform to EMC standards for immunity or susceptibility to interference.

Of course, part of the problem arises from confusion over the meaning of CE marking. The letters 'CE' appear on many products that are traded in the single market in the European Economic Area and nowadays in other territories as well. CE stands for '*Conformité Européene*', implying conformity to European technical standards, but on some products the same two letters can alternatively mean 'Chinese Export' (with no implication of conformity). It's little wonder then that consumers and retailers alike are misled.

The buck stops where?

Many LED lamps made abroad enter the UK at the Suffolk port of Felixstowe, where Suffolk Trading Standards make spot checks on consignments they intercept. According to principal officer Carol Garrett, '76% of LED lighting products tested and assessed were found to be unsafe or non-compliant.'

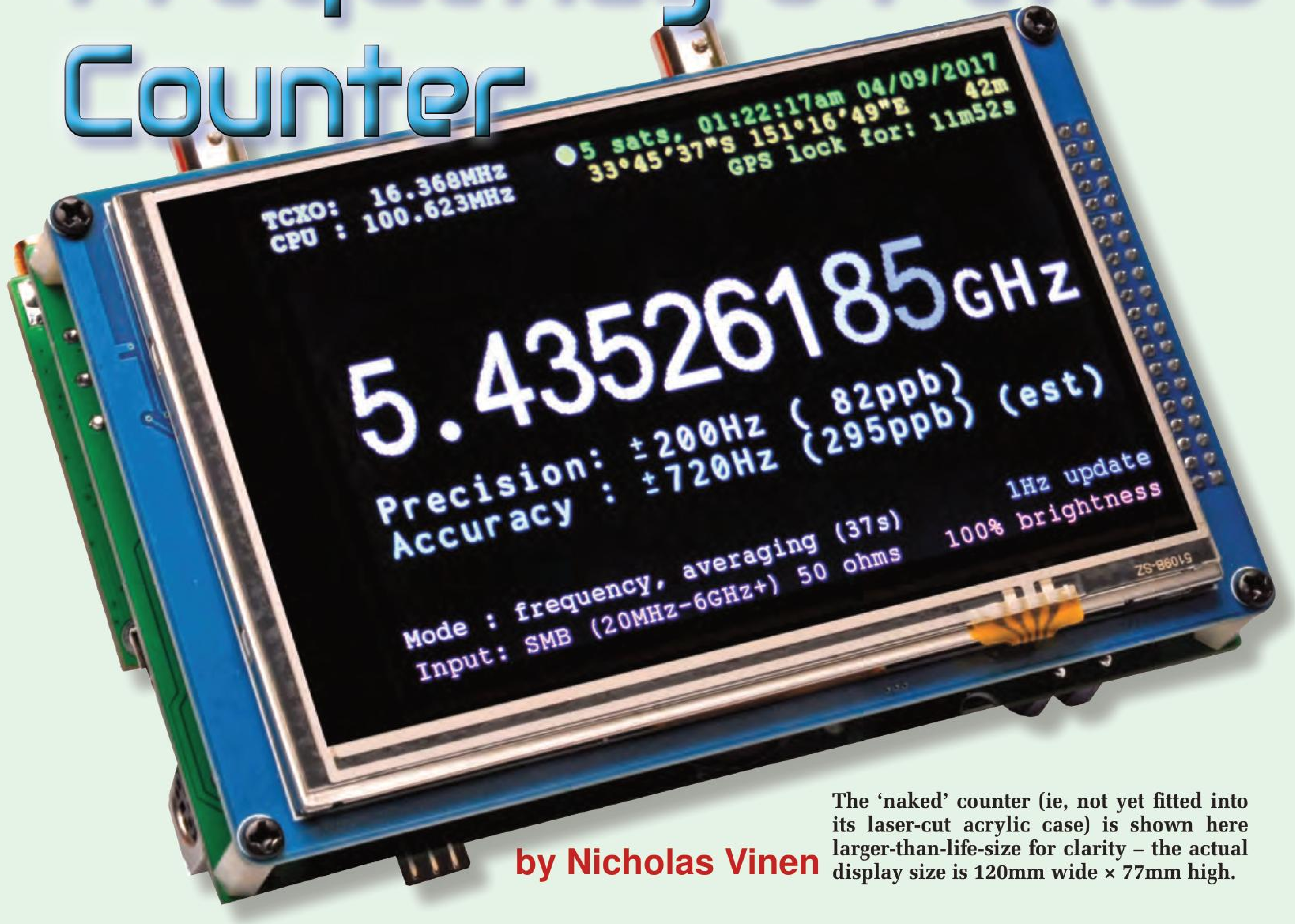
So, are we right to curse Chinese manufacturers for making sub-standard products? Actually no, because these manufacturers are governed by Chinese regulations, not European directives, and they make products for a global marketplace. The responsibility to ensure that imported items are manufactured in compliance with EU standards and labelled correctly lies with the importer, not the manufacturer. Your retailer is responsible for selling you a product that's conformant, safe and fit for purpose. If it upsets your radio reception, return it to the seller for a refund (make sure you keep the receipt when you buy it). Contact your local trading standards office if you encounter resistance or need further advice.

Top tips

For a 60W equivalent bulb, try the own-brand Wilko Filament Classic Frost that's sold in Wilko stores. For a 94W equivalent try the Osram from Robert Dyas. It's much brighter than a 100W incandescent but noticeably custard-yellow, although not unpleasantly so. Most Philips LED bulbs are blameless, as are most Diall ones from B&Q stores. Other brands are reliable, but the products mentioned above have been pronounced interference-free in tests.

More advice: always keep the sales receipt, in case the bulb fails soon after installation or despite your best endeavours, the recommended brands have changed supplier. Although retailers don't make it clear, the electronics in these lamps generate heat and need good air circulation. Fitting these bulbs with the 'cap' (base, or socket end) upwards halves their life. Using them in an enclosed fitting halves their life again. Not many people know that!

6GHz+ Touchscreen Frequency & Period Counter


TCXO: 16.368MHz
CPU : 100.623MHz
5 sats, 01:22:17am 04/09/2017
33°45'37"S 151°16'49"E 42m
GPS lock for: 11m52s
5.43526185GHz
Precision: ±200Hz (82ppb)
Accuracy : ±720Hz (295ppb) (est)
1Hz update
100% brightness
Mode : frequency, averaging (37s)
Input: SMB (20MHz-6GHz+) 50 ohms

The 'naked' counter (ie, not yet fitted into its laser-cut acrylic case) is shown here larger-than-life-size for clarity – the actual display size is 120mm wide × 77mm high.

by Nicholas Vinen

We haven't seen the equal of this all-new 6GHz (actually 6GHz+) design anywhere – built up or build-it-yourself. It's based on the famous Micromite Plus Explore 100 module to give you a superbly easy-to-read display, along with touchscreen control – and it has an optional GPS module to give you even more amazing accuracy. Check out the features and specifications opposite and tell us if we're wrong! This is one design that we are obviously very proud of – just as you will be when you build it.

This new design supersedes the *2.5GHz, 12-digit Frequency Counter* we described in the January and February 2014 issues of *EPE*. That was a great performer for its time and has been very popular, with many built. But this new counter is not just better – it's dramatically better!

It has greatly improved performance – for a start, it has more than twice the maximum frequency of the earlier design and a much lower minimum frequency.

Furthermore, instead of a row of LED displays, we also made the jump to using a large, touchscreen LCD. It not only shows the frequency/period display, but also all the user controls are now ON SCREEN – no more searching for the right pushbuttons!

The touchscreen functions are provided by a Micromite Plus Explore 100 module, designed by Geoff Graham and Graeme Rixon and described in the September and October 2017 issues.

Parts were getting hard to find

We realised the time to update the old design had come – not just because some of the parts used were becoming difficult to source, but also because it's a bit of a monster, needing a large instrument case and spread across two large PCBs with 26 ICs.

The *2.5GHz, 12-digit Frequency Counter* had selectable gating periods of one, 10, 100 or 1000 seconds. These periods correspond to its update rate, with the longer periods giving greater resolution. It was a bit tedious waiting for 1000 seconds (about 17 minutes) to get a reading, but that's necessary if you want 1Hz resolution at frequencies over 1GHz.

This new design can provide similar resolution at around 10 digits. However, because more of the actual frequency counting is done in software (on the more powerful PIC32 processor), it will give much faster display updates.

Incidentally, we didn't think there was much point going to 12 digits because you would need a time source accurate to within one part per *trillion* to have any confidence in the result, and even with GPS disciplining that's unrealistic.

This new design can also handle much lower frequencies/longer periods than its predecessor, down to around 0.01Hz (10mHz) compared to 10Hz.

It's also more sensitive, able to operate with signals down to just millivolts, over much of its frequency range.

The display will show the applied frequency almost immediately, with an indication of the reading precision, and the reading will then be progressively refined, reflected in a slowly improving precision figures over a few minutes.

So you don't need to wait for 17 minutes to get a reading; you just need to wait until the indicated precision is good enough for your situation and then make a note of the reading. If you don't need extreme precision, you can choose a faster update rate, with the reading changing several times per second.

High precision is great, but you also need good accuracy in this sort of instrument – briefly, precision indicates the repeatability of a measurement while accuracy indicates how closely it relates to reality.

Temperature-compensated crystal oscillator plus GPS option!

We're using a temperature-compensated crystal oscillator (TCXO) frequency reference to provide good accuracy 'out-of-the-box', with the option of GPS-disciplining to give even better long-term results.

Overall operating concept

This new *Frequency Counter* features the *6GHz+ Prescaler* that we published in the May 2018 issue. This provides the high frequency input and it has a separate input to handle the lower frequencies.

The *Frequency Counter* block diagram is shown in Fig.1 and gives the basic layout, showing how it is able to accurately measure the frequency of either of the inputs, shown at left.

The low-frequency input can handle signals of 0.01Hz-50MHz with a sensitivity of around 1mV RMS and a switchable load impedance of either 1MΩ or 75Ω, switched by the reed relay and transistor, as shown in Fig.1. The high-frequency input can handle signals of around 20MHz-6GHz, with a sensitivity of a few millivolts and a load impedance of 50Ω.

The low-frequency signal is buffered by high-speed op amp IC9 and then amplified and squared up by high-speed comparator IC6. The output of IC6 is then fed to the timer 1 clock input pin on the Explore 100 module. The PIC32 has five internal 16-bit timers, with timers 2/3 and 4/5 able to be paired up to form 32-bit timers.

We're using timer 1 in this case because it's asynchronous (ie, operates independently from the PIC32's own oscillator) and so can handle signals up to about 50MHz. The other timers can only operate up to about 18MHz (according to the data sheet). Note that the Micromite also has an output pin which can enable or disable the output of IC6; this will become important later.

The high-frequency input is fed to two wide-band monolithic microwave amplifier ICs (MMICs), IC1 and IC2, connected in series for extra gain. The amplified signal then passes to a high-frequency divide-by-five stage (IC3) and into a programmable divider with a division ratio of between 2 and 256, before also being squared up and fed to the timer 4/5 clock input pin of the Explore 100.

The combination of the two dividers gives an overall division ratio of 10-1280, controlled by eight digital outputs from the Explore 100 module. Thus, the Explore 100 can set the division ratio fairly high for high-frequency signals, eg, 6GHz÷512, or 11.718MHz , while using a lower division ratio for lower frequency signals, to give better resolution and/or faster updates.

As with IC6, the output of IC5 can be enabled or disabled by the Explore 100 via one of its digital outputs.

So the Explore 100 can measure the pulses resulting from either input, but it needs a precise measurement interval in order to accurately calculate and display the frequency. Its internal 100MHz clock runs off a PLL (phase-locked loop) which is driven by a 20MHz crystal and internal oscillator amplifier. But this won't be *exactly* 20MHz, and will change with temperature and over time.

Reference frequencies

To solve this, we are using a more accurate 16.368MHz TCXO as the frequency reference – IC7. Unfortunately,

Micromite parts and competition!

We recommend you make **micromite.org** your first port of call when shopping for all Micromite project components. Phil Boyce, who runs micromite.org, can supply kits, programmed ICs, PCBs and many of the sensors and other devices mentioned in recent articles. ***Plus, do see page 20 for an exciting Micromite competition!***

Outstanding features and specifications

Display: 800 × 480 pixel, 24-bit colour LCD with adjustable backlight brightness

Frequency ranges: 10mHz-50MHz (low frequency input), 6MHz-6GHz+ (high frequency input); typically counts up to 7GHz

Sensitivity: typically <10mV RMS below 3.5GHz and <125mV RMS, 3.5-7GHz

Resolution: normally seven digits, increasing to 10 after 10 minutes with long-term averaging enabled

Accuracy: ±2.5ppm initial tolerance (±0.00025% or ~5.5 digits) +1ppm/year; better with GPS unit after automatic calibration

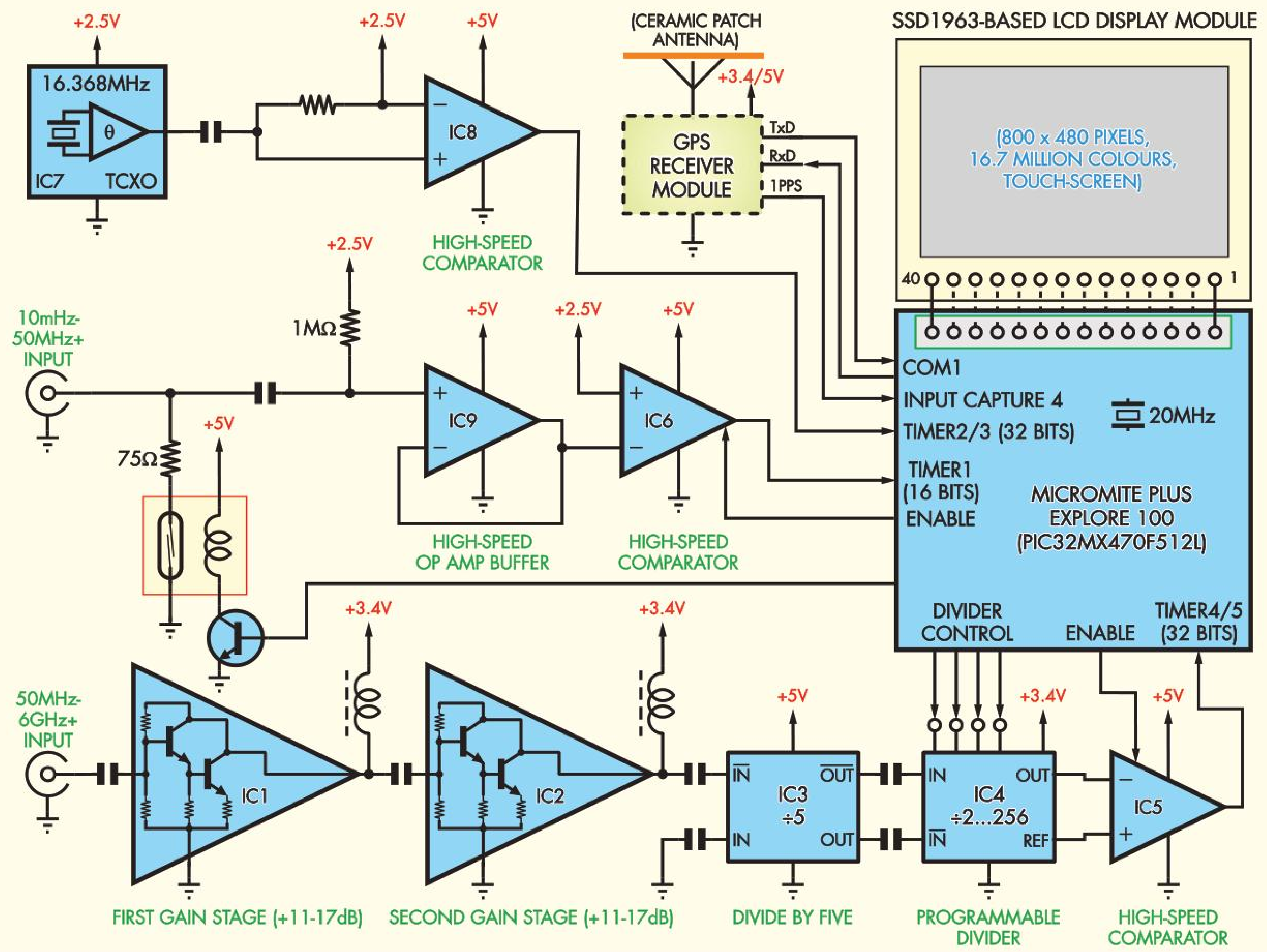
Input impedance: selectable, 75Ω or 1MΩ (low-frequency input), fixed, 50Ω (high-frequency input)

Update rate: selectable, 1-5Hz

Modes: frequency or period with either constant updates or long-term averaging

TTL reference output: selectable, 1Hz/1kHz reference frequencies or measured frequency divided by 1000

Power: 6V DC 1A plugpack OR can operate from 5V DC (eg USB) supply or computer output for use in field



+2.5V
16.368MHz
IC7
TCXO
+2.5V
+5V
IC8
HIGH-SPEED COMPARATOR
(CERAMIC PATCH ANTENNA)
+3.4/5V
GPS RECEIVER MODULE
TxD
RxD
1PPS
SSD1963-BASED LCD DISPLAY MODULE
(800 x 480 PIXELS, 16.7 MILLION COLOURS, TOUCH-SCREEN)
40
1
+2.5V
10mHz-50MHz+ INPUT
1MΩ
+5V
+2.5V
+5V
IC9
IC6
75Ω
+5V
HIGH-SPEED OP AMP BUFFER
HIGH-SPEED COMPARATOR
COM1
INPUT CAPTURE 4
TIMER2/3 (32 BITS)
20MHz
TIMER1 (16 BITS) ENABLE
MICROMITE PLUS EXPLORE 100 (PIC32MX470F512L)
DIVIDER CONTROL
ENABLE
TIMER4/5 (32 BITS)
+3.4V
+3.4V
50MHz-6GHz+ INPUT
IC1
IC2
+5V
IC3 ÷5
IN
OUT
IN
OUT
+3.4V
IC4 ÷2...256
IN
OUT
IN
REF
+5V
IC5
FIRST GAIN STAGE (+11-17dB)
SECOND GAIN STAGE (+11-17dB)
DIVIDE BY FIVE
PROGRAMMABLE DIVIDER
HIGH-SPEED COMPARATOR

Fig.1: block diagram of the Micromite-based *Touchscreen Frequency Meter* (power supply not shown). The signal at the low-frequency input is buffered and then squared up by a high-speed comparator before being fed to the Explore 100 module.

The signal at the high-frequency input is divided down by a factor of between 10 and 1280 before also being squared up and fed to the Explore 100. The TCXO and GPS reference signals can be used to gate either signal and provide an accurate frequency measurement.

because the Explore 100 is a pre-built module, we can't use this to drive the main clock, at least, not without butchering the board.

Instead, we square up the output of this oscillator (it's a sinewave) using IC8 and feed this to the clock input for timer 2/3. Not only does this give us an accurate time reference, but also we can use two of the PIC32's 'output compare' units (OC1 and OC2) to automatically gate the outputs of IC5 and IC6 for a precise number of pulses from IC8.

For example, if we reset timers 1-3 and then set the output compare unit to drive the enable pin low (on) for 1,638,400 pulses of timer 4/5, we can measure exactly 100ms worth of pulses from both inputs.

The TCXO is quite stable and precise, with an initial tolerance of ±2.0ppm and only ±0.5ppm variation from –10°C to +70°C and ±1.0ppm drift per year. This translates to an initial accuracy of around ±0.00025% and a long-term accuracy of around ±0.001%.

Say you are measuring a signal of exactly 2.4GHz. That means you should get an initial measurement of between 2,399,994,000Hz and 2,400,006,000Hz. If you have a very precise reference frequency to calibrate the unit (essentially, allowing you to measure the actual frequency of the TCXO and then compensate for it), you could probably get it to within a few hertz.

That's pretty good, but what if you don't have a precise reference frequency and what about temperature variations and drift over time? Well, with the addition of a low-cost GPS module, the TCXO can be automatically calibrated ('disciplined').

Its 1PPS input is connected to the Input Capture 4 pin, which automatically stores a copy of the contents of the timer 2/3 counter each time it goes high. We can then extend this to a 64-bit value in software and keep, say, 3600 values, or one hour's worth of GPS 1PPS timestamps.

The individual intervals between GPS 1PPS pulses are not necessarily precise, but averaged over the long term they should give us a very good reference.

If we calculate the difference between the TCXO counter value one hour ago versus the most recent pulses and divide the result by 3600, that gives us the exact TCXO frequency, averaged over the last hour, to within one or two hertz.

So, the upshot is, if you fit the counter with a GPS module, provided it is getting enough signal from the satellites to get a good lock, you should get very accurate readings without needing to do any calibration.

The software can save the calibration value into Flash memory so that even if you only power up the counter for a short time (eg, to make a measurement), it can be reasonably accurate. You just need to leave it powered up for a while every now and then to let it adjust its own calibration.

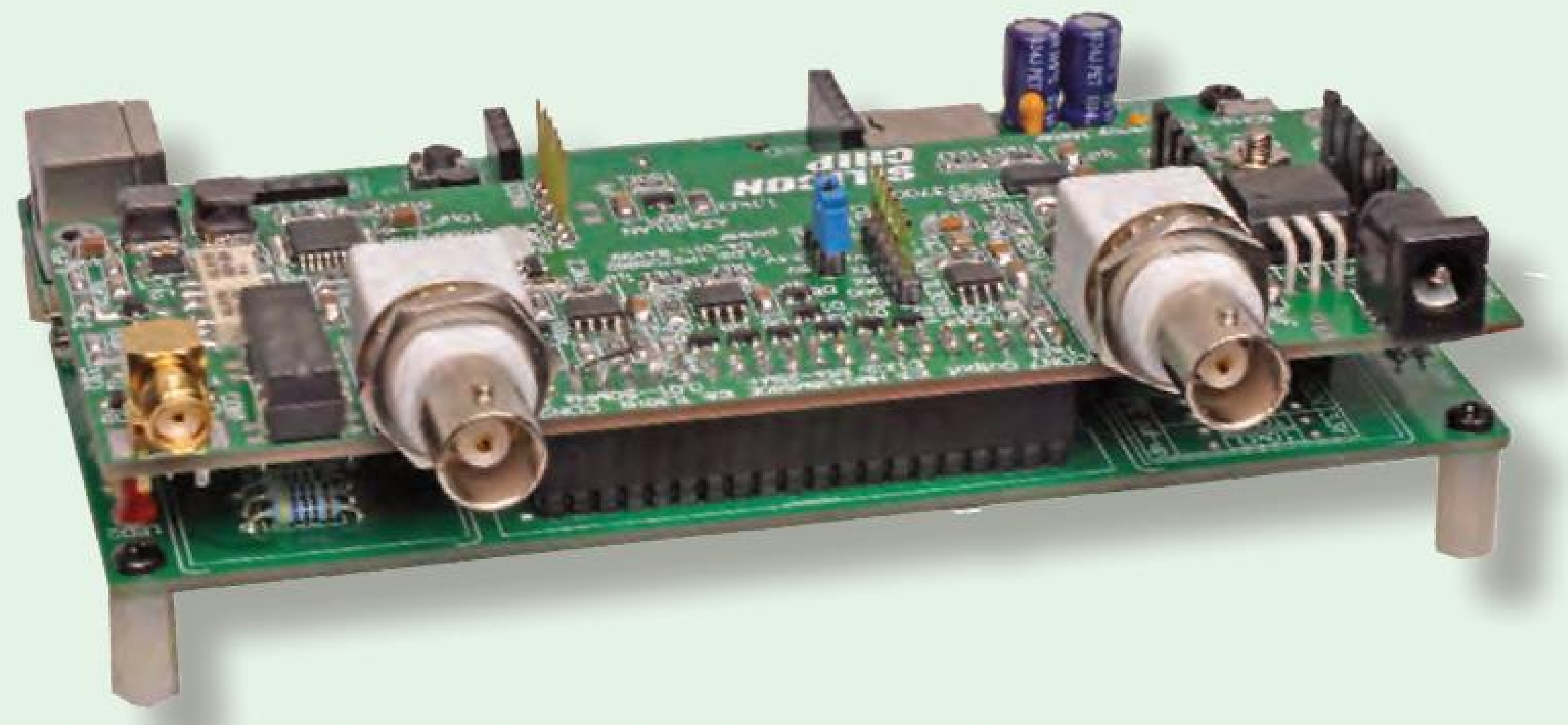
By connecting up the GPS unit's serial console to communication port 1 on the Explore 100, we can check whether it has a proper satellite lock before using the 1PPS signal, and we can also display information on the LCD, such as the number of satellites in view, UTC time/date and the current location (latitude/longitude/altitude).

Frequency display

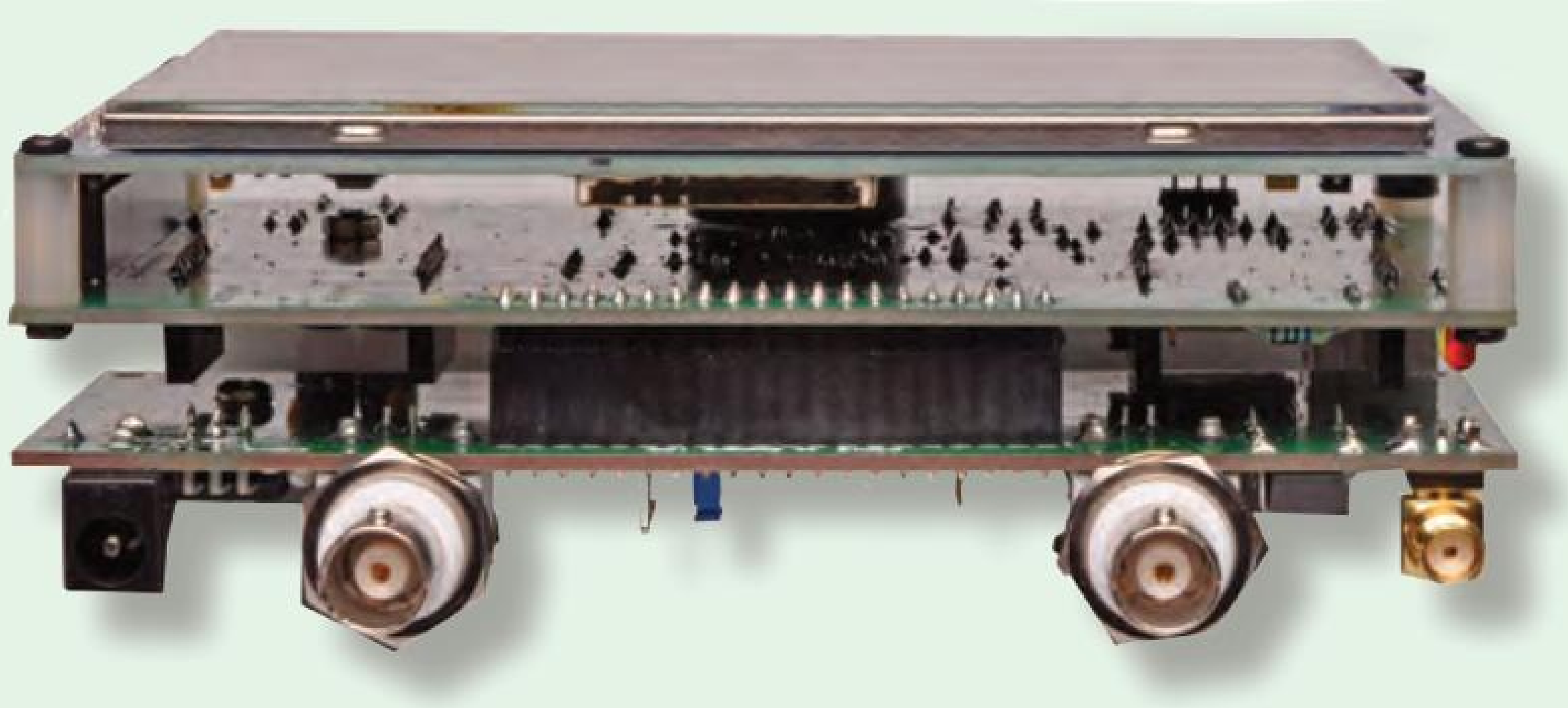
The job of the *Frequency Counter* is – of course – to display the frequency of the currently selected input, and you can use the touchscreen to select the input you want to measure and the measurement period.

The software then sets up the timers appropriately and continuously measures, computes and displays the result in large letters on the LCD. It can even format the result into a nice, human-readable value like '2.38754GHz' or '434.56MHz'.

The Explore 100 can tell whether you have a GPS unit attached by monitoring the serial port. If you do, it will automatically perform long-term TCXO calibration and use the calibrated value when measuring the input frequencies. Otherwise, it will either use the default TCXO frequency (16.368MHz) as the reference, or a calibrated value, if you program one in. It can also show the frequency reading as a period value instead. That is most useful for lower frequencies. It's just a matter of inverting the calculations.



This 'upside-down' photo shows how the frequency counter PCBs assemble one on top of the other. The I/O connectors are on the opposite side of the Explore 100 board than the touchscreen . . .



. . . as shown in this photo of the completed unit, with the LCD display module mounted on stand-offs. Because of this arrangement, the input and output connectors are along the top of the module.

Circuit description

Fig.2 shows the complete circuit, minus the Explore 100 itself, which plugs in via 40-pin DIL connector CON3. The *Frequency Meter* plugs into the top side of the Explore 100 PCB, with the input, output and power connectors accessible via the top edge. The 5-inch LCD touchscreen is mounted on the opposite side of the Explore 100.

Most of this circuit corresponds to the block diagram of Fig.1, except for the power supply, which was not shown. Starting with the low-frequency (50MHz) input, this is fed in via BNC connector CON2. When set for a 75Ω input impedance, this is simply achieved by reed relay RLY1 connecting a 75Ω termination resistor across the socket.

The signal is AC-coupled with a 10µF ceramic capacitor and biased to 2.5V using a 1MΩ resistor. Thus, with RLY1 de-energised, the input impedance is around 1MΩ, although there is no DC path to ground. A dual series schottky diode, D12, clamps the signal so that it is between –0.2V and +5.2V. It is then fed to the pin 3 non-inverting input of buffer op amp IC9.

This is a Linear Technology LTC6268HS8 which has a –3dB bandwidth of 350MHz when set for unity gain (as it is here). So it will have negligible attenuation of signals below 50MHz. It has a very low input bias current of typically 3fA (yes, femtoamps – that's 0.000000000000003A!) at room temperature, which is the primary reason why we're using it here, as a buffer for IC6.

Basically, the input bias current of comparator IC6 is so high that it would cause several volts to appear across the 1MΩ bias resistor if it was connected directly to IC6's input. If we lowered the value of this 1MΩ resistor to solve the bias current issue, that would both load up the signal source and also increase the minimum frequency which could be measured. The easiest solution is to buffer the signal.

As well as a very low input bias current, IC9 also needs a low input offset voltage, otherwise this would reduce the sensitivity of the frequency meter due to a mismatch between the quiescent voltage at pins 2 and 3 of IC6, which normally should both be very close to 2.5V, thus only a small signal from CON2 is needed to cause the output of IC6 to toggle.

IC9 also has a low noise of 4.3nV÷$\sqrt{\text{Hz}}$, which equates to about 80µV over the quoted 350MHz unity-gain bandwidth. Too much noise could cause inaccurate frequency readings because it would be superimposed on the signal and so could cause extra 'zero crossings'.

Noise at this input of IC6 is rejected by providing a small amount of hysteresis, due to the 10MΩ resistor between the pin 7 non-inverted output and pin 2 non-inverted input, combined with the 390Ω resistor from output pin 6 of IC9. Given that the output swing of IC6 is 5V, that gives a hysteresis of around 200µV (5V × 390Ω ÷ 10MΩ).

As this is higher than the noise from IC9, it should result in a zero reading with no signal applied, but will hardly affect the sensitivity.

The reason for the 390Ω series resistor between IC9 and IC6 is to match the source impedance for the two inputs (pins 2 and 3) so that the bias current flowing into these inputs will cause a similar shift across both resistors, so the error will mostly cancel out.

The output from pin 7 of IC6 is fed to pin 22 of CON3 (input RC14 [pin 74] of the PIC32) via a 1kΩ resistor with a parallel 100pF capacitor. The 1kΩ resistor is there to limit current when the output of IC6 is high since it will go up to +5V, while the PIC32 only has a 3.3V supply rail. The 100pF capacitor ensures that high-frequency signals will not be significantly attenuated by the input capacitance of the PIC32 pin.

High-frequency signal path

Higher frequency signals are fed into CON1, an SMB socket. As noted above, most of the following circuitry is based on that of the *6GHz+ Prescaler* from the May 2018 issue. Its circuit diagram was shown on pages 14 and 15 of that issue.

The signal is clamped to around 1V peak-to-peak by schottky diodes D1 and D2 and then AC-coupled to the input of MMIC IC1, which provides about 11-16dB gain, depending on frequency. Its input and output impedances are both matched to 50Ω.

The power supply for IC1 is fed into its pin 3 output via RF choke L1, with a snubber/Zobel network from pin 3 to ground to improve its stability and provide better sensitivity between about 4-4.5GHz.

The output signal is then fed to another, identical amplification stage based on IC2/L2, giving a total gain of around 22-32dB. The amplified signal is then AC-coupled again, via a 10nF capacitor, to the inverting input pin 3 of IC3, a 6GHz divide-by-five counter which uses high-electron-mobility-transistor technology (HEMT) . Its non-inverting input is tied to ground with another 10nF capacitor, as we are using it with a non-differential signal.

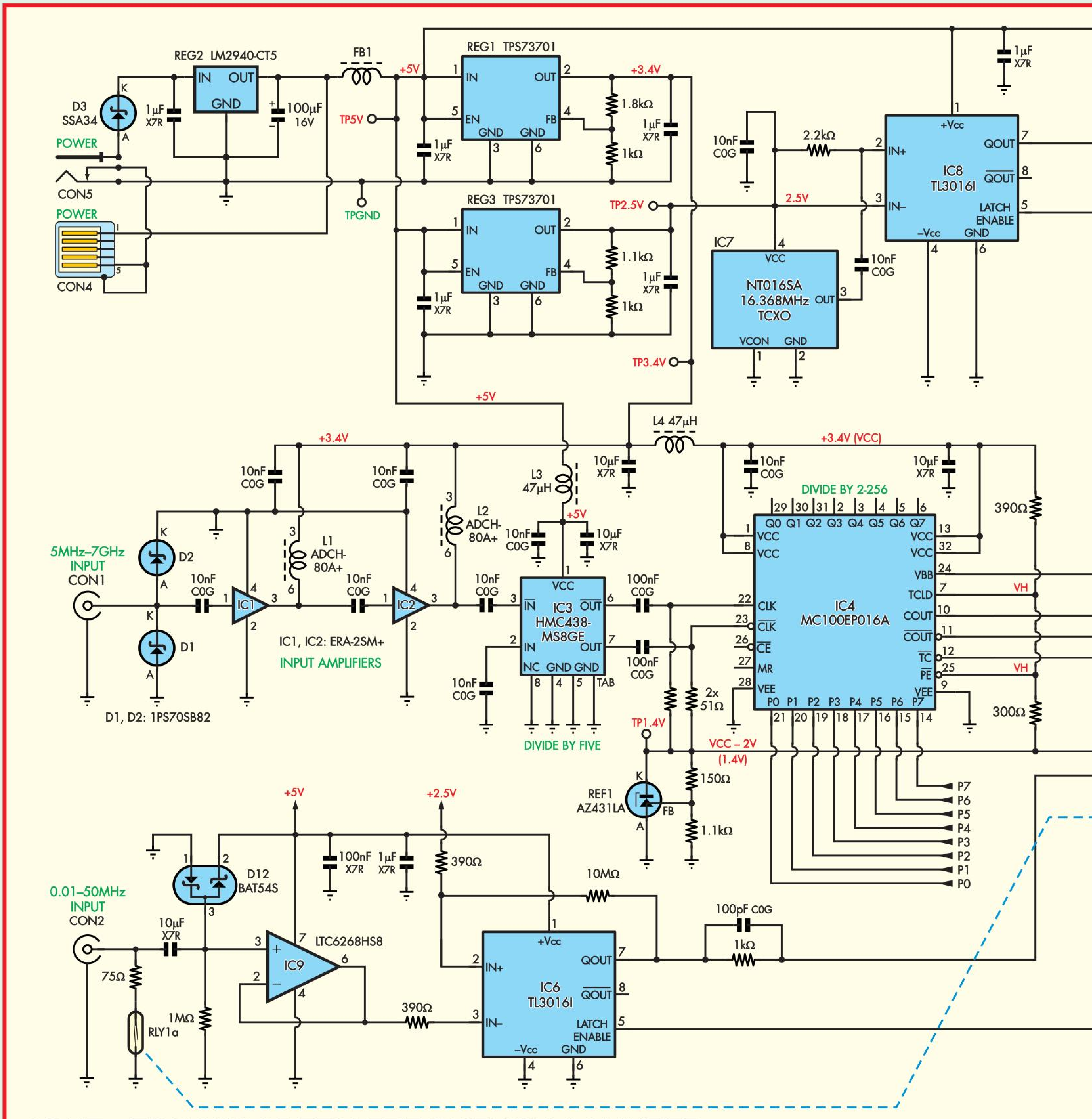
The differential output signal, at one-fifth of the input frequency, appears at output pins 6 and 7 and these signals are then AC-coupled to the differential inputs of IC4 using 100nF capacitors.

IC4 is an emitter-coupled logic (ECL) 1.2GHz programmable counter. Its inputs are terminated to a supply rail 2V below its V_{CC} pin via 51Ω resistors, as suggested in the data sheet.

Setting the division ratios

IC4 contains an internal 8-bit counter. Every time it exceeds 255 (11111111 in binary) to zero, the counter value is reset to the value provided externally on the P0-P7 inputs. If this pre-load value is, say, 254 then the counter will roll over on every second input pulse (254, 255, 254, 255, ...) and thus it essentially acts as a divide-by-two device. Or you could pre-load 252 and it would act as a divide-by-four, and so on.

Each of the P0-P7 inputs has an internal pull-down resistor, so the PIC32 microcontroller determines the division ratio by


REG2 LM2940-CT5
IN OUT GND
D3 SSA34
K A
1µF X7R
100µF 16V
POWER
CON5
POWER
CON4
FB1
+5V
TP5V
TPGND
REG1 TPS73701
IN OUT EN FB GND GND
+3.4V
1.8kΩ
1kΩ
1µF X7R
REG3 TPS73701
TP2.5V
1.1kΩ
TP3.4V
IC7
NT016SA 16.368MHz TCXO
VCC OUT VCON GND
10nF C0G
2.2kΩ
2.5V
IC8 TL3016I
+Vcc IN+ IN– QOUT QOUT LATCH ENABLE –Vcc GND
L4 47µH
+3.4V (VCC)
10µF X7R
10nF C0G
DIVIDE BY 2-256
390Ω
300Ω
5MHz–7GHz INPUT CON1
D1 D2
D1, D2: 1PS70SB82
IC1 IC2
IC1, IC2: ERA-2SM+ INPUT AMPLIFIERS
L1 ADCH-80A+
L2 ADCH-80A+
L3 47µH
IC3 HMC438-MS8GE
VCC IN IN OUT OUT NC GND GND TAB
DIVIDE BY FIVE
100nF C0G
2x 51Ω
IC4 MC100EP016A
Q0 Q1 Q2 Q3 Q4 Q5 Q6 Q7
VCC VBB TCLD COUT COUT TC PE VEE CLK CLK CE MR
P0 P1 P2 P3 P4 P5 P6 P7
VH
TP1.4V
VCC – 2V (1.4V)
150Ω
REF1 AZ431LA
FB
1.1kΩ
+5V
+2.5V
D12 BAT54S
0.01–50MHz INPUT CON2
10µF X7R
75Ω
RLY1a
1MΩ
IC9 LTC6268HS8
100nF X7R
1µF X7R
390Ω
10MΩ
IC6 TL3016I
100pF C0G
1kΩ

6GHZ+ TOUCHSCREEN FREQUENCY COUNTER

pulling up those inputs which need to be set to one (high). This is done in each case via a BAV99 dual series diode, which drops the 3.3V high level from the PIC32 outputs to around 2.3V, a suitable high level for an ECL device.

The MC100EP016A data sheet says that with a 3.3V supply, a high level is defined as between 2.075V and 2.42V. This arrangement may seem a bit crude but it works well.

IC4 has three outputs, COUT (pin 10), $\overline{\text{COUT}}$ (pin 11) and $\overline{\text{TC}}$ (pin 12). All three are terminated to the V_{CC}–2V (1.4V) rail via 51Ω resistors.

We found the $\overline{\text{TC}}$ output gave the cleanest waveform, so we're feeding this to high-speed comparator IC5. It compares it to the reference voltage from pin 24 (V_{BB}), which is halfway between the ECL high and low thresholds. The result is a 5V square wave at output pin 7, which can then be fed to the PIC32, again with a 1kΩ series current-limiting resistor paralleled with a 100pF capacitor.

Reference oscillator

The temperature-compensated crystal oscillator (TXCO, IC7) runs from a dedicated 2.5V rail since this is what it requires and providing it with a regulated rail will minimise any frequency shift due to supply variation.

It has a 10nF bypass capacitor and its sinewave output at pin 3 (around 0.8V peak-to-peak) is AC-coupled to the non-inverting input (pin 2) of comparator IC8, via another 10nF capacitor.

This signal is DC-biased to 2.5V via a 2.2kΩ resistor and the same 2.5V bias is applied to inverting pin 3 so that the square wave from pin 7 will have a duty cycle close to 50%.

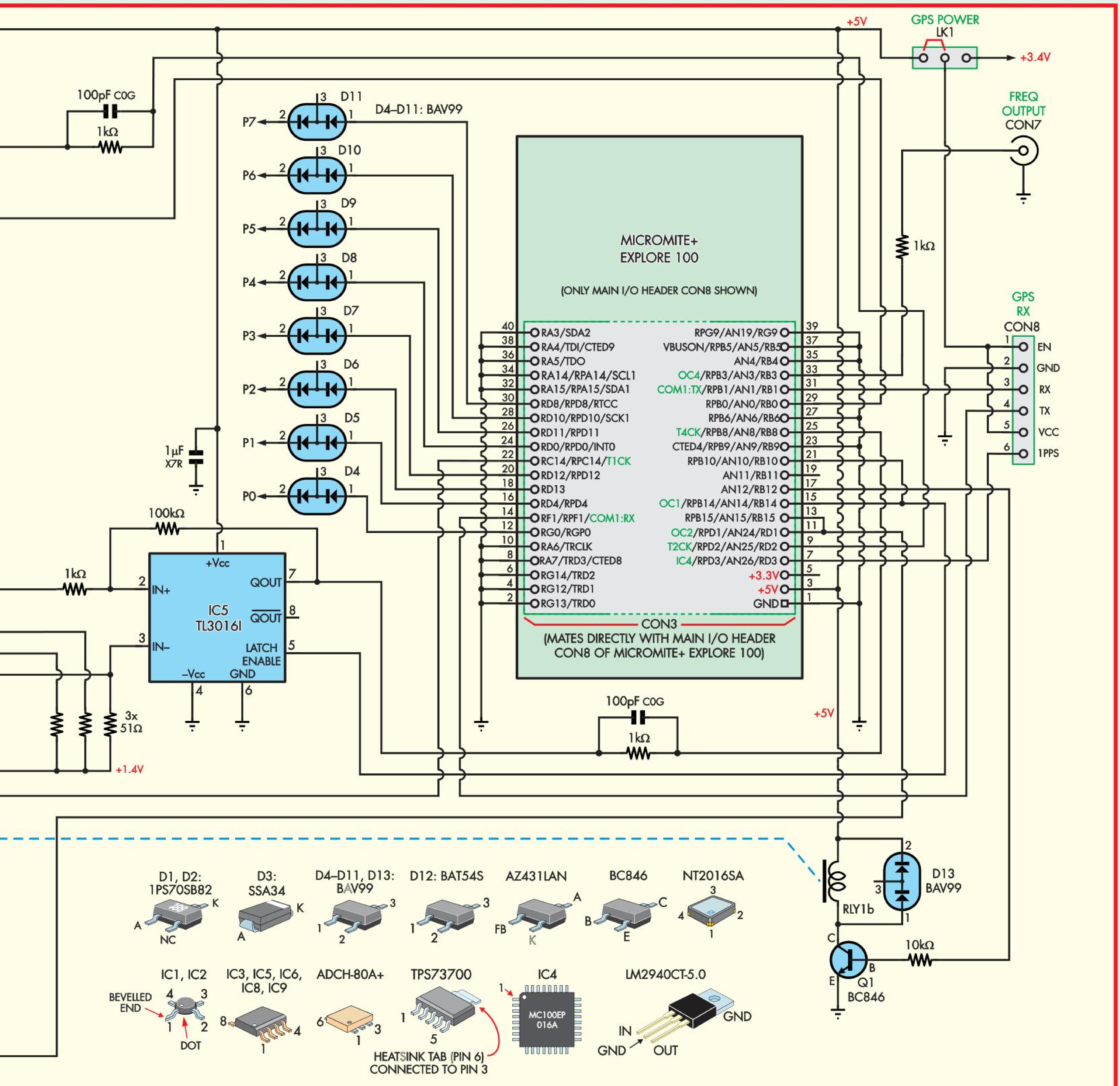

+5V
GPS POWER
LK1
+3.4V
FREQ
OUTPUT
CON7
100pF C0G
1kΩ
D11
D4–D11: BAV99
P7
D10
P6
D9
P5
D8
P4
D7
P3
D6
P2
D5
P1
D4
P0
1μF
X7R
100kΩ
1kΩ
MICROMITE+
EXPLORE 100
(ONLY MAIN I/O HEADER CON8 SHOWN)
RA3/SDA2
RA4/TDI/CTED9
RA5/TDO
RA14/RPA14/SCL1
RA15/RPA15/SDA1
RD8/RPD8/RTCC
RD10/RPD10/SCK1
RD11/RPD11
RD0/RPD0/INT0
RC14/RPC14/T1CK
RD12/RPD12
RD13
RD4/RPD4
RF1/RPF1/COM1:RX
RG0/RGP0
RA6/TRCLK
RA7/TRD3/CTED8
RG14/TRD2
RG12/TRD1
RG13/TRD0
RPG9/AN19/RG9
VBUSON/RPB5/AN5/RB5
AN4/RB4
OC4/RPB3/AN3/RB3
COM1:TX/RPB1/AN1/RB1
RPB0/AN0/RB0
RPB6/AN6/RB6
T4CK/RPB8/AN8/RB8
CTED4/RPB9/AN9/RB9
RPB10/AN10/RB10
AN11/RB11
AN12/RB12
OC1/RPB14/AN14/RB14
RPB15/AN15/RB15
OC2/RPD1/AN24/RD1
T2CK/RPD2/AN25/RD2
IC4/RPD3/AN26/RD3
+3.3V
+5V
GND
CON3
(MATES DIRECTLY WITH MAIN I/O HEADER
CON8 OF MICROMITE+ EXPLORE 100)
1kΩ
GPS
RX
CON8
EN
GND
RX
TX
VCC
1PPS
+Vcc
IN+
IN–
QOUT
QOUT
LATCH
ENABLE
–Vcc
GND
IC5
TL3016I
3x
51Ω
+1.4V
100pF C0G
1kΩ
+5V
RLY1b
D13
BAV99
10kΩ
Q1
BC846
D1, D2:
1PS70SB82
D3:
SSA34
D4–D11, D13:
BAV99
D12: BAT54S
AZ431LAN
BC846
NT2016SA
A
K
NC
FB
B
C
E
IC1, IC2
IC3, IC5, IC6,
IC8, IC9
ADCH-80A+
TPS73700
IC4
LM2940CT-5.0
BEVELLED
END
DOT
MC100EP
016A
HEATSINK TAB (PIN 6)
CONNECTED TO PIN 3
IN
GND
OUT
GND

Fig.2: complete circuit for the *Frequency Meter*, with the Explore 100 'black box' at right. The low-frequency (up to 50MHz) input signal path is shown at lower left, while higher frequency signals are fed into the configurable prescaler shown at centre left. The linear power supply is at upper left and provides 5V, 3.4V and 2.5V rails and there is also a 1.4V (3.4V – 2V) rail for ECL logic termination.

The clock signal is then fed to the T2CK/RD2 pin of the PIC32 in the Explore 100, via another paralleled 1kΩ resistor and 100pF capacitor pair. The enable pin (pin 5) of IC8 is driven from the RB0 output, but in practice it's enabled pretty much all the time.

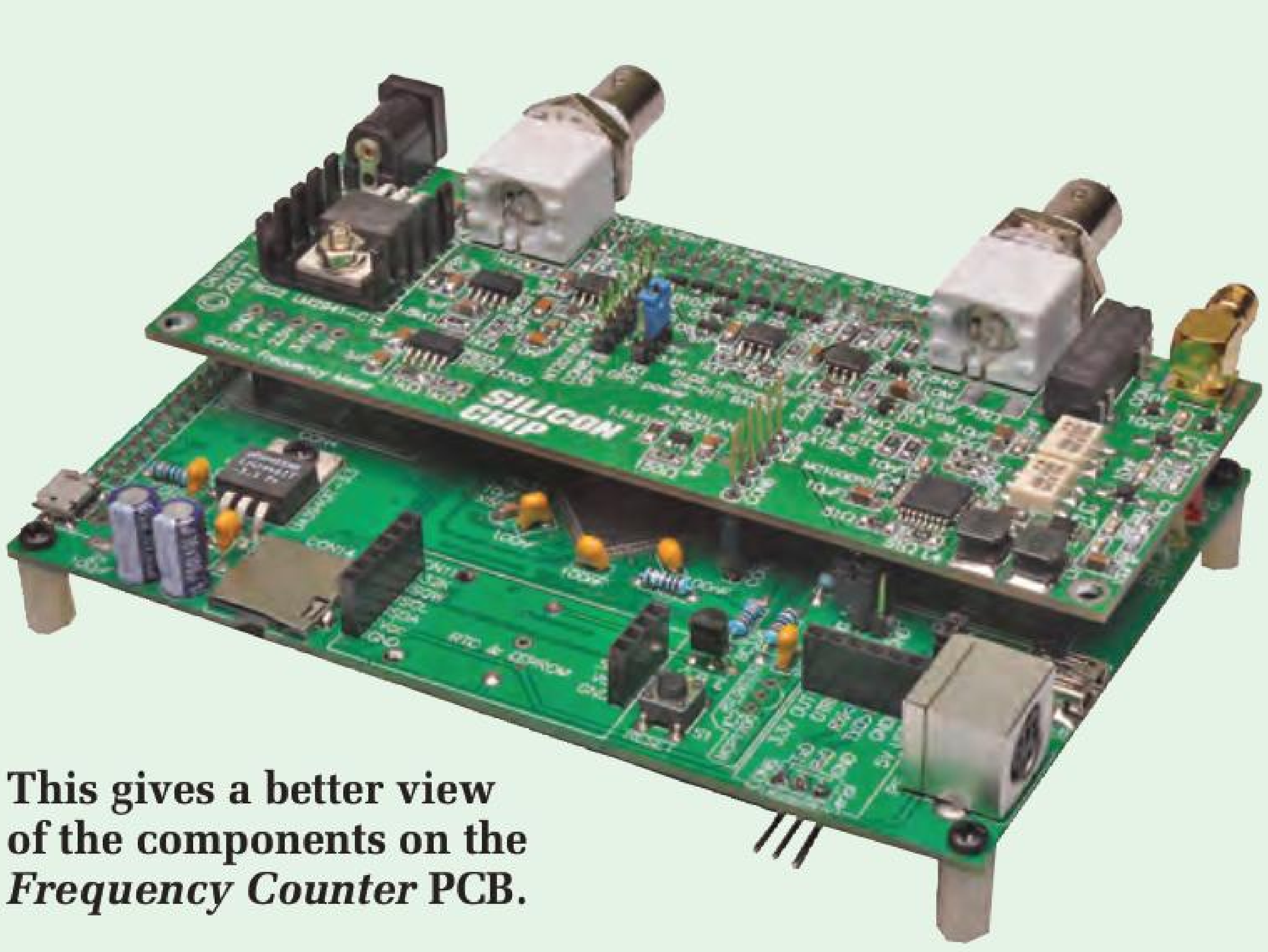
Power supply

Power normally comes from a 6V DC regulated plugpack and the current drain is normally close to 1A. This is regulated to 5V by 1A low-dropout regulator, REG2, which has a 1μF input bypass capacitor and 100μF output filter capacitor for stability. We're using an LDO (low dropout) regulator to reduce dissipation, since it means we can have a 6V DC regulated input and still draw at least 1A without it dropping out.

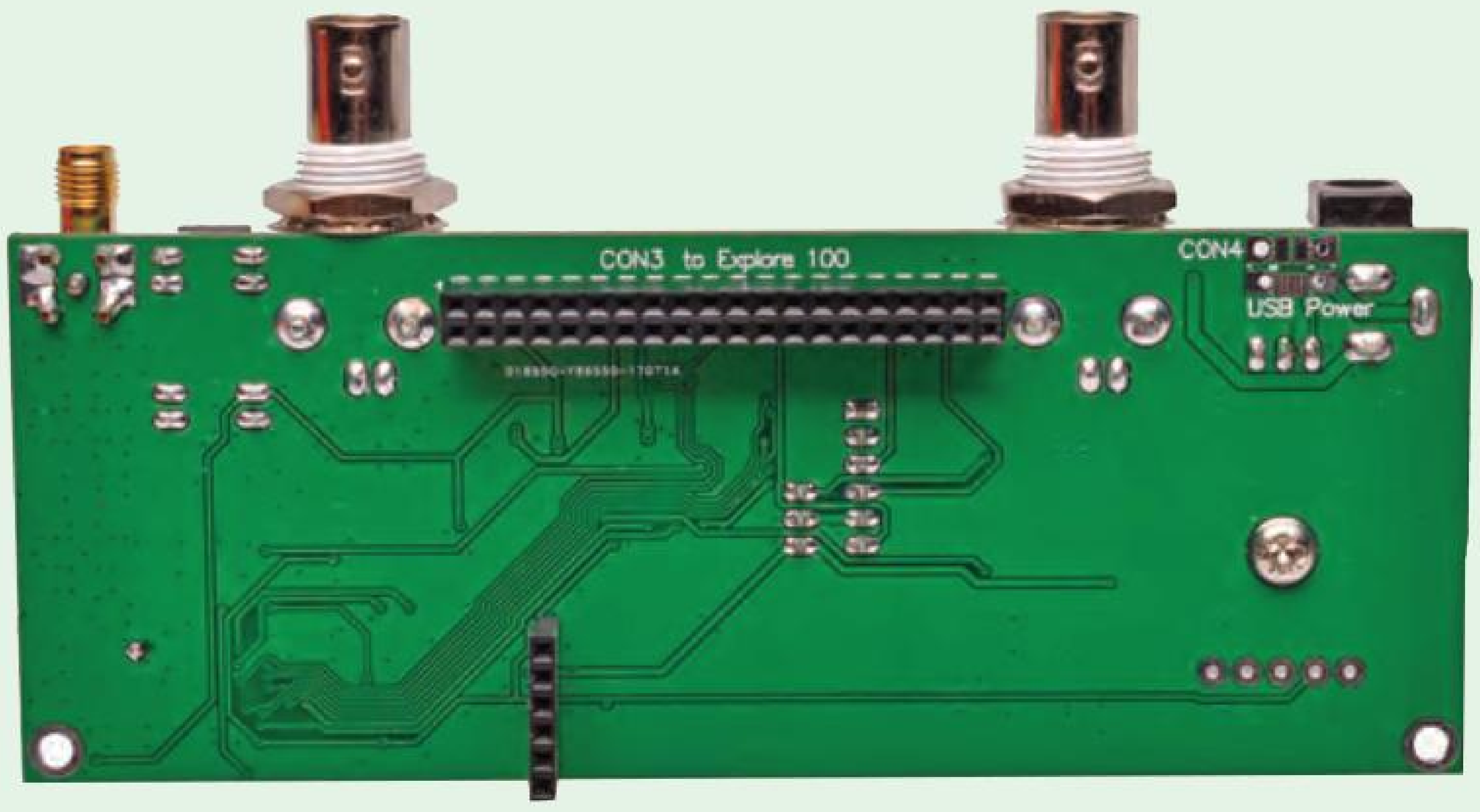
It does need a small heatsink though, as it will dissipate 1W continuously, and more if the incoming supply is much above 6V. Its output passes through ferrite bead FB1, so that any high-frequency noise produced by the circuit does not get radiated out of the plugpack leads.

The 5V rail powers the Explore 100 module, including the LCD touchscreen backlight, as well as high-frequency divider IC3, op amp IC9 and the reed relay, RLY1. It can also be used to power the GPS module, if required. This 5V rail is also fed to LDO adjustable regulators REG1 and REG3. These identical devices have different programming resistors so that they produce 3.4V DC and 2.5V DC regulated rails.

The 2.5V rail is for the TCXO (IC7) and is also used in a few places as a 5V half-supply reference for DC biasing the inputs of high-speed comparators IC6 and IC8. The 3.4V rail



This gives a better view of the components on the *Frequency Counter* PCB.



The underside of the *Frequency Counter* PCB (the top board in the photo at left). The only 'components' on this side are the 2 × 20-pin female header which mates with the plug on the lower board and the 6-pin ICSP pass-through header.

powers amplifiers IC1 and IC2, ECL divider IC4 and can also be used to power the optional GPS module. As explained earlier, REF1 derives the 1.4V rail (3.4V–2V) which is used to terminate IC4's clock inputs and its outputs.

Finally, output connector CON7 can provide a 3.3V square wave output which is fed from the RB3/OC4 pin of the PIC32 on the Explore 100 module. This can be driven by its Output Compare module, producing a PWM waveform derived from one of the timers. As such, it can be set to produce a frequency which is a fraction of one of the input frequencies, for use as a trigger or reference frequency.

Or it can provide a fixed reference frequency derived from the TCXO or a 1PPS or 1kHz reference derived from the GPS module. This is selected using the touchscreen.

Software basics

We won't go into a lot of detail here, but it's helpful to understand how the software is able to perform frequency measurements using the circuit presented. In essence, we have eliminated all the house-keeping logic circuitry used in the previous 12-digit frequency counter and these functions are now performed by the software.

As stated, the squared-up signal from the low-frequency input is applied to the clock input for asynchronous timer 1 (T1CK), while the 16.368MHz reference oscillator signal is applied to the timer 2/3 clock input (T2CK) and the frequency-divided signal from the high-frequency input goes to the timer 4/5 clock input (T4CK).

Since timer 1 is a 16-bit timer, with the maximum specified input frequency of 50MHz, it could roll over every 1.3ms (2^{16}÷50MHz, or 65536÷50,000,000).

That isn't too fast, and fortunately the Micromite BASIC firmware exposes the timer 1 interrupt to CFUNCTIONS. So we can set up an interrupt handler for this roll-over in C and use that to increment another 16-bit register, to form a 32-bit timer. It handles a maximum of 763 interrupts per second.

We also need to set up timer pairs 2/3 and 4/5 in a CFUNCTION. The fact that we're using all five timers in this manner means that we can't use any of MMBasic's timing functions (eg, DELAY, TICK) as they will no longer work properly, but we can provide our own timing functions written in C.

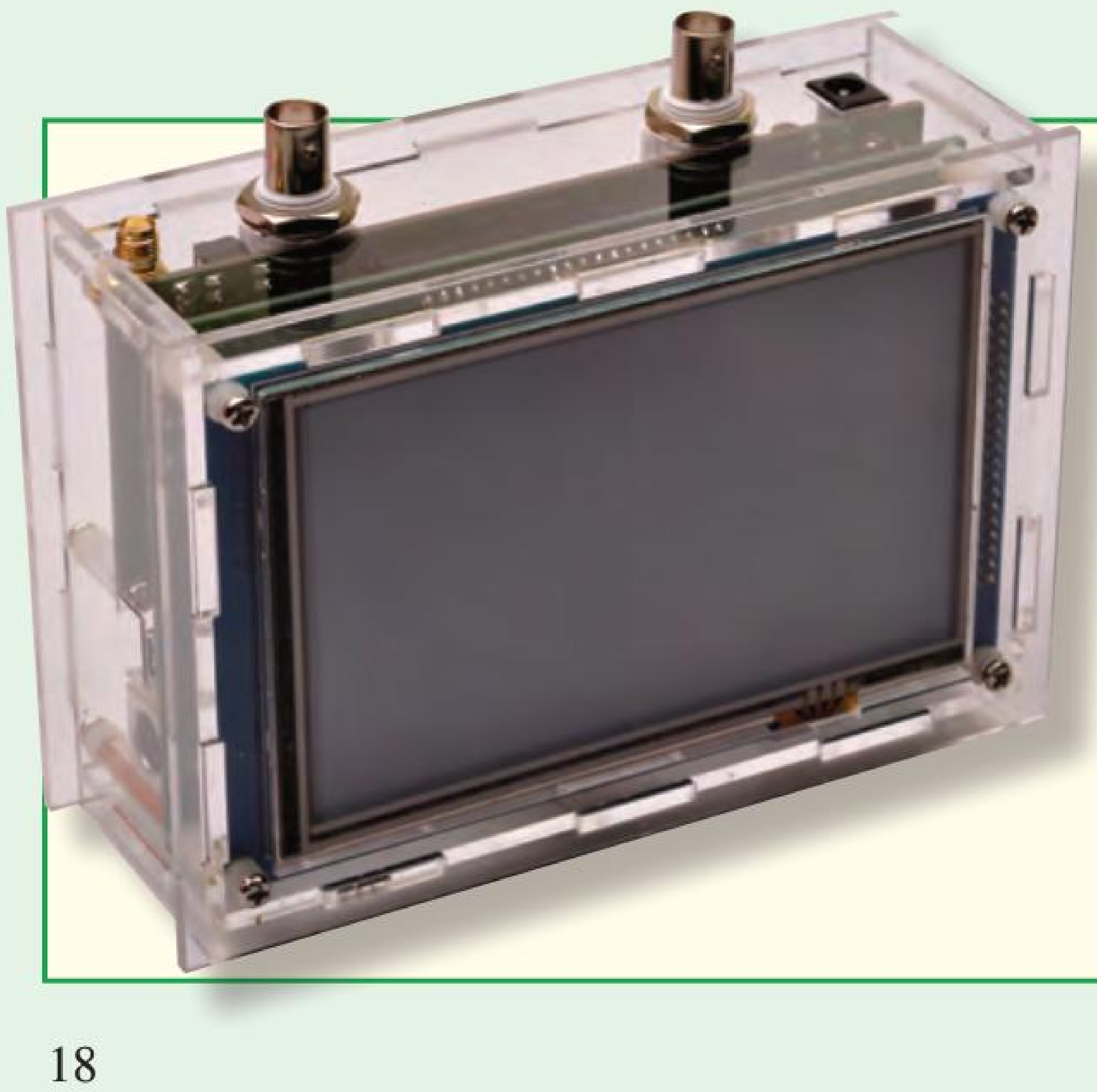
While we've found the synchronous timers (ie, timers 2-5) will operate OK for signals up to about 24MHz, the PIC32's specifications indicate a minimum period of 55ns, which equates to 18.18MHz.

The signal driving timer 4/5, from the programmable divider, can be kept under this frequency limit by briefly measuring the input frequency using the maximum divider value of 1280, which gives a maximum frequency of under 5MHz with a 6GHz input, then computing the lowest possible divider value for that frequency to give the best resolution without exceeding the timer's limit.

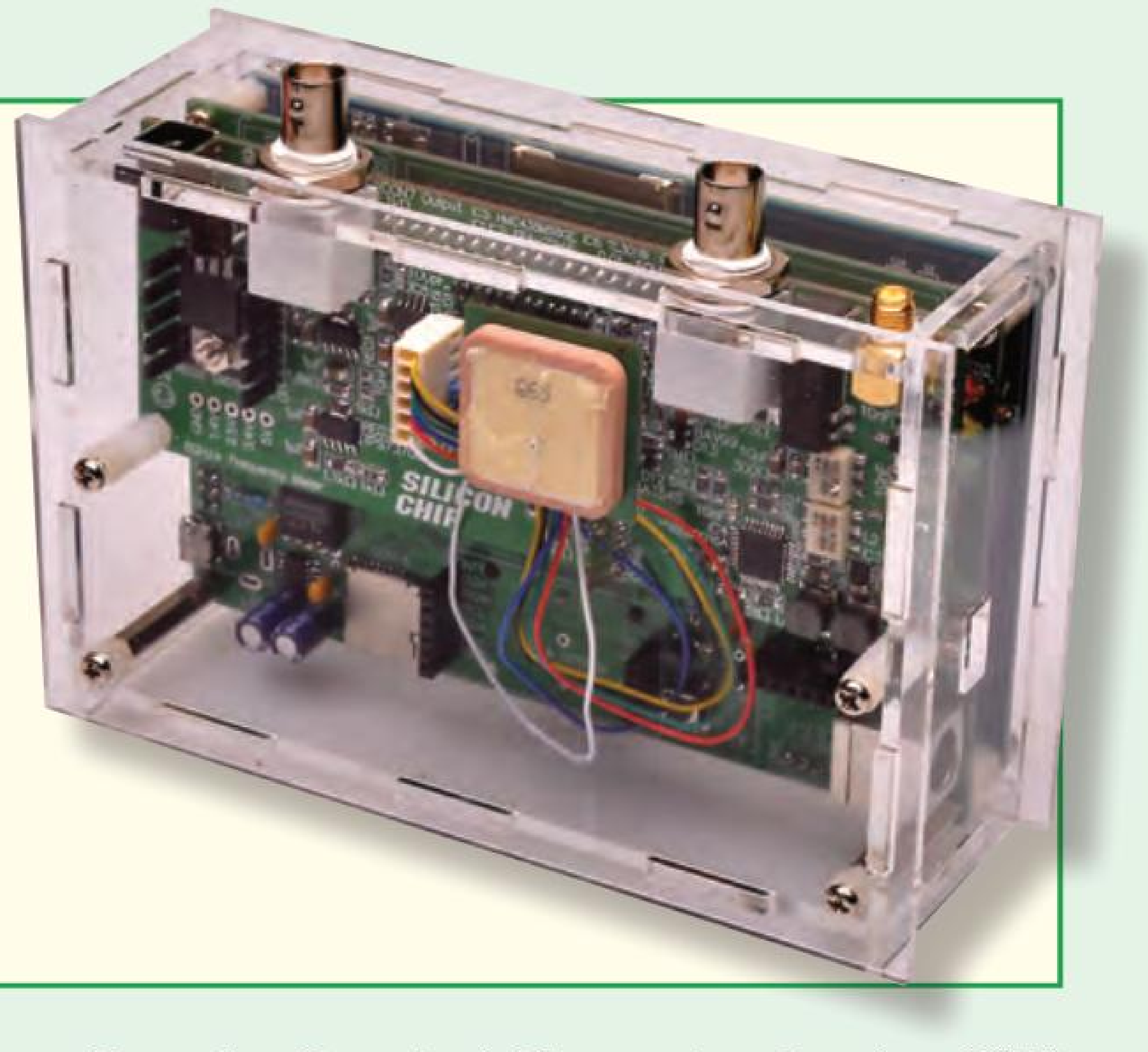
For example, if the input frequency is 2.4GHz, the unit will measure 1.875MHz (2.4GHz÷1280) and it can then set the division ratio as low as 132, which gives 18.18MHz (2.4GHz÷132), just on the device's limit. In practice, a slightly higher division ratio would be used to account for measurement errors and so on.

Now, if the unit is set to measure the frequency at the 0.01Hz-50MHz input, pin 11 (RD1) will initially be set high, disabling the output pulses from IC6, while timer 1 is zeroed. RD1 will then be configured as OC2, controlled by the second Output Control unit. This compares the value of timer 2/3 to a fixed value and drives OC2 low while the timer value is below the specified value.

This allows us to set the 'window' period during which timer 1 runs to a fixed period based on the frequency of the TCXO. So if we set the comparison value to 1,638,600 then



Here's what the new *Frequency Counter* will look like next month, when we put it into its purpose-designed laser-cut acrylic case. A front cut-out gives access to the 5-inch touchscreen display. It's not just a sensational performer, it looks sensational too!



timer 1 will be active for 100ms and we can determine its frequency with just some simple calculations.

Similarly, when measuring the frequency from the input with the prescaler, we can gate the output using OC1 (RB14), which also has its output state determined by the value of timer 2/3.

We do have to be careful with this one though, because we're gating the output of the prescaler, not the input. That could lead to errors in the frequency measurement, so ideally, we should measure the time between OC1 going low and the first pulse from the prescaler, and also bring OC1 low manually once counting is finished and measure the time until the next pulse.

These figures can then let us 'fine tune' the measurement, to get a more accurate figure for the input frequency. The software uses the fact that RD1 (OC2) is connected to general purpose I/O pin RB15 while RB14 (OC1) is also connected to GPIO RB10. So we can set up pin change interrupts on RB14 and RB10, so that an interrupt routine is triggered when the OC1/OC2 outputs change state.

GPS-based automatic calibration

All the other tasks (eg, updating the screen, switching the relay) are handled in BASIC. That just leaves the unit's use of the GPS 1PPS signal to provide more accurate measurements.

We have the 1PPS output of the GPS unit connected to the RD3 I/O pin, which is configured for the Input Capture function (IC4).

This automatically stores the 32-bit value in timers 2 and 3 on the rising edge of each GPS unit output pulse. The software can periodically check the input capture interrupt flag and if set, it can then retrieve this 'timestamp' value and store it in a large memory array.

It's then just a matter of 'crunching' the numbers in this memory array, which gives the number of TCXO pulses at one-second intervals over a long period, to calculate the actual TCXO frequency and apply this correction to frequency measurements made using its timebase. By using long-term measurements, we eliminate GPS signal jitter errors.

By the way, we mentioned earlier that we have to do our own timing in the code and we have a couple of options for doing this.

The Micromite code doesn't give us access to an interrupt for timer 2, unfortunately, so we can't generate a periodic interrupt based on its value. But we certainly can 'busy wait' (or poll) based on its value to delay the code for an approximate time period.

We can also set up either timer 1 (when using timers 4/5 for measurement) or timers 4/5 (when using timer 1 for measurement) to run off the system clock and then delay based on these values. But in practice, our code can afford to block the main loop when it needs a delay, so simply polling the contents of timers 2 and 3 is good enough.

Parts

This is an advanced high-speed design and needs the parts specified. Many of those listed opposite are Digi-Key references, but other major suppliers like Mouser, element14 and RS should also stock them. You can look up the parts on the Digi-Key website to get the manufacturer's part number and then search other suppliers.

Next month

That's enough to absorb for one month! Next month, we will go through the PCB assembly process, putting it together with the Explore 100 and getting the software up and running. We'll also go over testing and calibration procedures and describe fitting it into a custom-made acrylic case.

Parts list – 6GHz+ Touchscreen Frequency Counter

Do pay special attention to device versions and packaging

1 Micromite Explore 100 module or kit (from micromite.org)
1 6V DC 1A+ regulated plugpack
1 double-sided PCB, available from the *EPE PCB Service*, coded 04110171, 134 × 51.5mm
1 set of laser-cut acrylic case pieces, available from the *EPE* online shop
2 ADCH-80A+ RF inductors
2 47µH 1A 6×6mm SMD inductors
1 5V DIL reed relay
1 low-resistance SMD ferrite bead, 3216/1206
1 6031-type flag heatsink (for REG2)
1 M3 × 8mm machine screw and nut (for REG2)
1 PCB-mount right-angle SMA connector, 6GHz+ (CON1)
2 PCB-mount right-angle BNC connectors (CON2,CON7)
1 20×2 female header, 2.54mm pitch (CON3)
1 PCB-mount DC barrel socket, pin diameter to suit plugpack (CON5, recommended) OR
1 micro USB SMD socket with locating pins (CON4)
1 6-pin female header with long pins, 2.54mm pitch (CON6, for ICSP pass-through)
1 6-pin polarised header, matching plug, 2.54mm pitch (CON8)
1 3-pin header, 2.54mm pitch, with shorting block (LK1)
1 GPS module (eg, VK2828U7G5LF) (optional but recommended)
2 25mm-long M3 tapped spacers
2 12mm-long M3 tapped spacers
2 M3 × 32mm machine screws
6 M3 × 10mm machine screws
4 M3 × 6mm machine screws
8 M3 nylon hex nuts
4 3mm ID, 6mm OD, 1mm-thick nylon washers

Semiconductors

2 ERA-2SM+ SMD MMICs
1 HMC438MS8GE, MSOP-8-PP
1 MC100EP016A programmable ECL counter, LQFP-32
3 TL3016I high speed comparators, SOIC-8 (IC5,IC6,IC8)
1 NT2016SA-16.36800 SMD TCXO
1 LTC6268HS8 500MHz op amp, SOIC-8 (IC9)
1 AZ431LAN voltage reference, SOT-23
2 TPS73701 adjustable LDO regulators, SOT-23-5
1 LM2940-CT5 LDO 5V regulator, TO-220 (REG2)
1 BC846 NPN transistor, SOT-23 (Q1)
2 1PS70SB82 UHF diodes, SOT-323
1 SSA34 3A schottky diode in DO-214AC/SMA package (or equivalent), (D3)
9 BAV99 dual series diodes, SOT-23 (D4-D11,D13)
1 BAT54S dual series schottky diode, SOT-23 (D12)

Capacitors (all SMD 3216/1206 6.3V X5R/X7R)

1 100µF 16V through-hole electrolytic
4 10µF 9 1µF 3 100nF
9 10nF 0805 5 100pF C0G/NP0 0805

Resistors (all SMD 2012/0805 1% unless noted)

1 10MΩ 1 1MΩ 1 100kΩ 1 10kΩ 1 2.2kΩ
1 1.8kΩ 2 1.1kΩ 7 1kΩ 3 390Ω 1 300Ω
1 150Ω 5 51Ω 2 33Ω 1 75Ω 1W 6432/2512 1%

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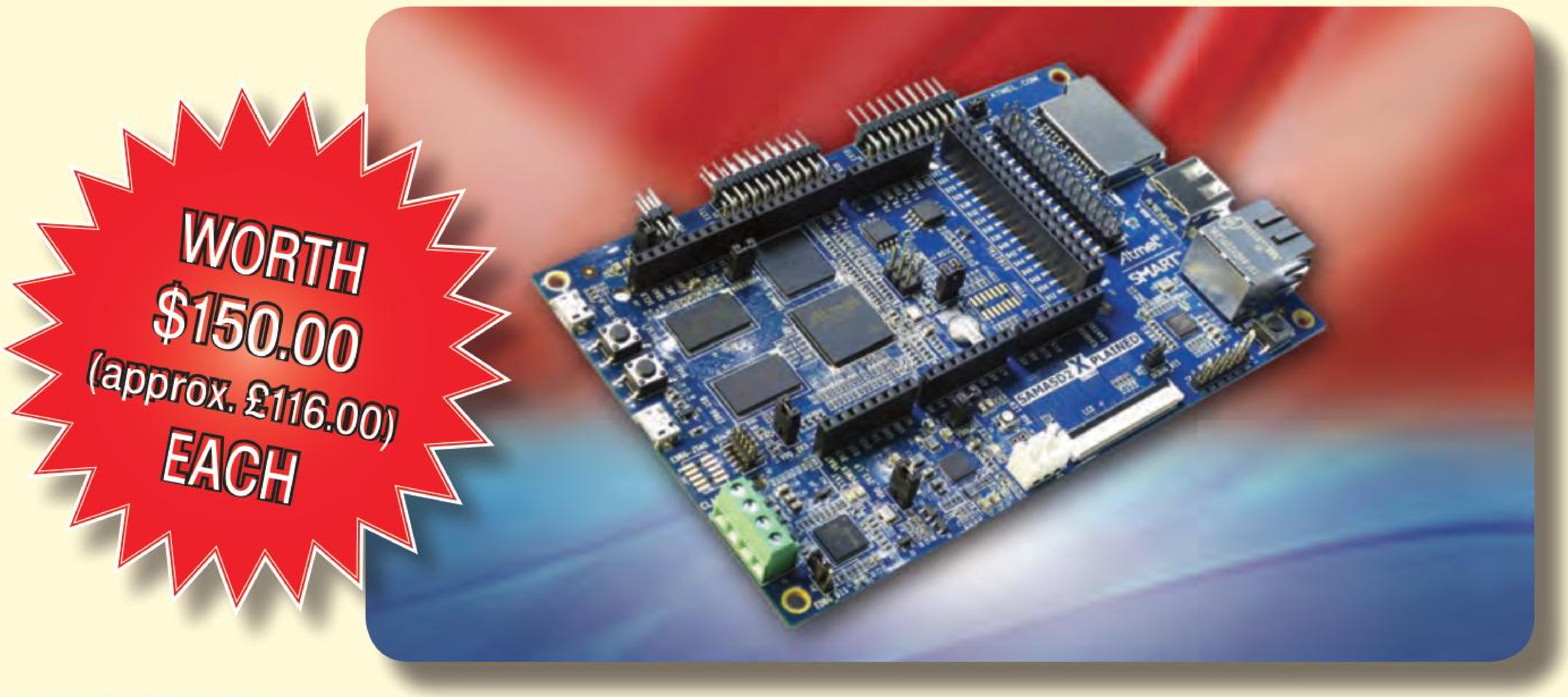
The SAMA5D2 is a high-performance, ultra-low-power, ARM Cortex-A5-processor-based MPU. The Cortex A5 processor runs at up to 500MHz and features the ARM NEON SIMD engine, a 128kB L2 cache and a floating-point unit. It supports multiple memory types, including latest-generation technologies such as DDR3, LPDDR3 and QSPI Flash. It integrates powerful peripherals for connectivity (EMAC, USB, dual CAN and up to 10 UARTs), plus user-interface applications such as a TFT LCD controller, PCAP and resistive touch controllers, class-D amplification, audio PLL and a CMOS sensor interface.

The devices offer advanced security functions to protect customer code and secure external data transfers. These include ARM TrustZone, tamper detection, secure data storage, a hardware encryption engine, on-the-fly decryption of code stored in external DDR or QSPI memory and a secure boot loader.

The SAMA5D2 Xplained Ultra board allows users to extensively evaluate, prototype and create application-specific designs. The board includes eMMC and DDR3 memory, as well as a rich set of connectivity options.

A Linux distribution and software package allows you to easily get started with your development; and connectors and expansion headers allows for easy customisation and quick access to leading-edge embedded features such as the Class D amplifier or capacitive touch controller (PTC).



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CLOSING DATE

The closing date for this offer is 31 October 2018.

3-Way Fully Adjustable Stereo Active Crossover for Loudspeakers

Part 2

by JOHN CLARKE

Last month, we described the circuitry and operation of our new *Active Crossover*. Now we continue with its construction – building the PCB, testing it, then putting it in its acrylic case for a truly professional finish.

This Active Crossover has true Hi-Fi performance, as shown in the specification panel and accompanying plots. Harmonic distortion is well below 0.001% across most of the audible frequency range, rising to only about 0.0015% at 20kHz. The combined frequency response of the three outputs is almost completely flat from 20Hz to 20kHz.

As you might expect, distortion is much higher when the bass limiter is actively limiting – at around 2% – but this is much lower than the distortion you would otherwise experience with a woofer driven into clipping, which is what the limiter is designed to prevent.

Channel separation is around –50dB and note that most of the crosstalk is due to the simple balance control and so this will not lead to any noticeable distortion.

Tracking of the high-pass and low-pass filter pairs is very good, as you can see from the relevant frequency response plots (Figs.17 and 18). Overall, this *Active Crossover* will have an insignificant effect on the signals passing through it and so will not 'colour' or degrade the audio signals. Ultimately, that means that the sound quality you get depends entirely on the amplifiers and speakers used.

The project itself is constructed using a single PCB, which is available from the *EPE PCB Service*, coded 01108171 and measuring 284 × 77.5mm. It comprises a mix of both through-hole and surface-mount components. Most are mounted on the top of the PCB but a few resistors and capacitors mount underneath.

The PCB and panels are designed to fit into a stand-alone case made from front and rear panel PCBs along with pre-cut 3mm black acrylic panels. Alternatively, you could fit the PCB in a 1U rack case but then you would need to come up with your own mounting and panel arrangements. And it's pounds to peanuts that it won't look as good as the acrylic case shown here!

Soldering SMDs

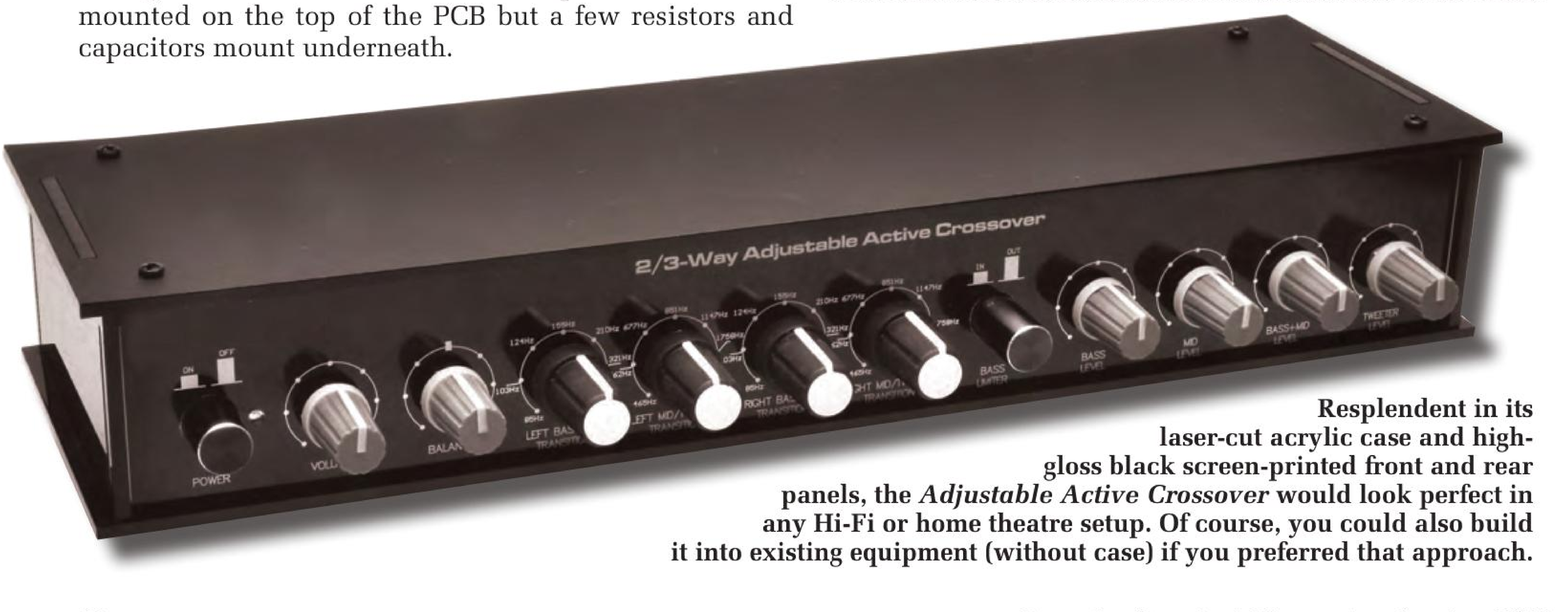
You will need a fine-tipped soldering iron bit, 0.71mm diameter solder, a good light and a magnifying glass or spectacles to solder the surface-mount components in place.

Begin by mounting the surface-mount ICs, all LM833 dual op amps. Each IC must be oriented correctly – note that the chamfered side is the pin 1-4 side of the IC.

The technique for soldering these in place is the same for all: locate the IC in position over its PCB pads and solder *one* corner pin. Check alignment and remelt the solder if the IC needs realignment.

When the IC is aligned correctly, solder the remaining pins. If you end up bridging adjacent pins, these can be cleared using solder wick.

Once all 25 ICs are soldered in, then align and solder the 100nF supply bypass capacitors (code 104) for each of these ICs. Check for a short circuit between each side of the 100nF



Resplendent in its laser-cut acrylic case and high-gloss black screen-printed front and rear panels, the *Adjustable Active Crossover* would look perfect in any Hi-Fi or home theatre setup. Of course, you could also build it into existing equipment (without case) if you preferred that approach.

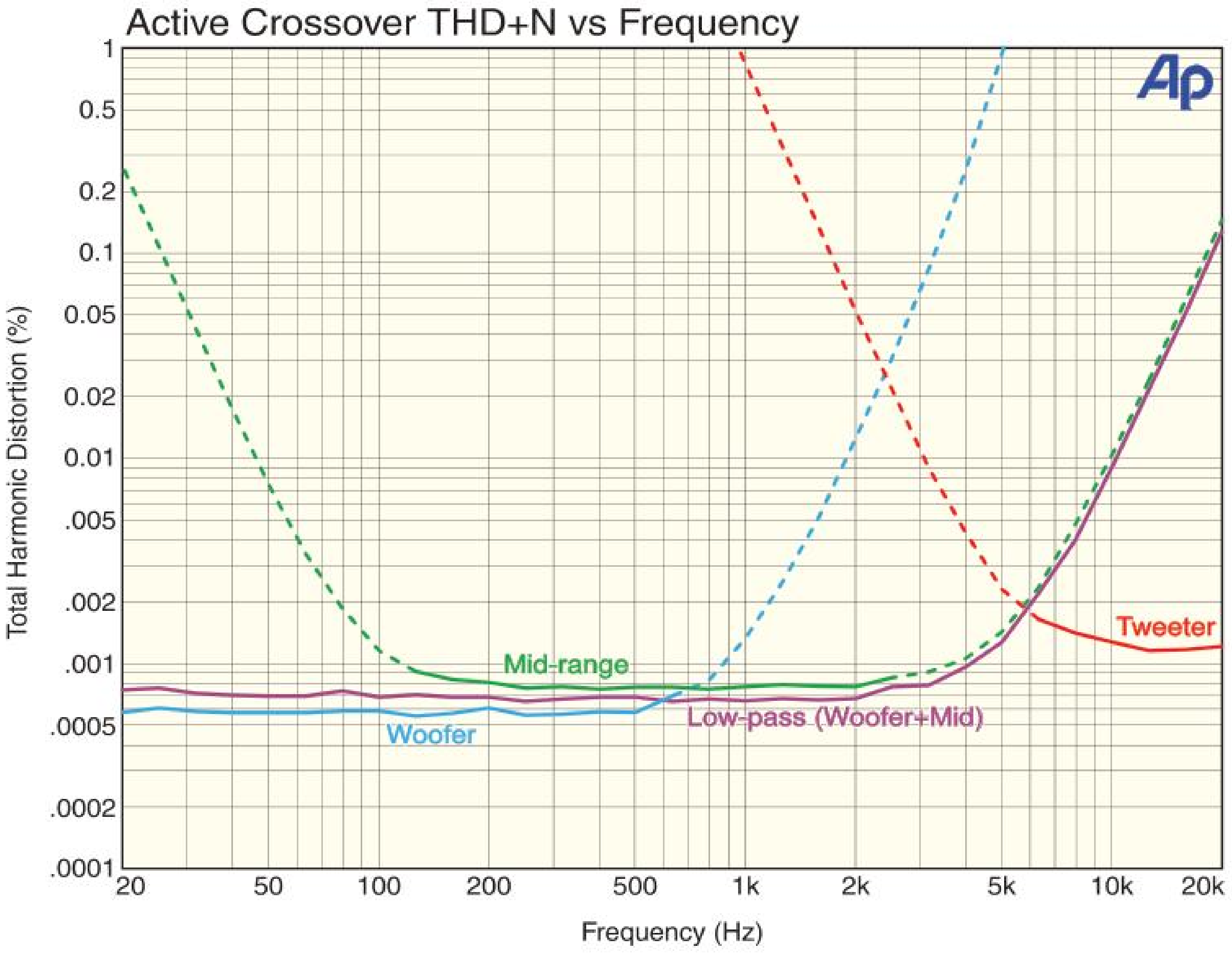


Fig.11: distortion plotted against frequency, with all four outputs measured independently. The dotted sections are where the amplitude of that output is dropping off, resulting in the distortion level appearing higher, due to diminishing signal-to-noise ratio. As you can see, at the frequencies where each output carries the majority of the signal, harmonic distortion is very low.

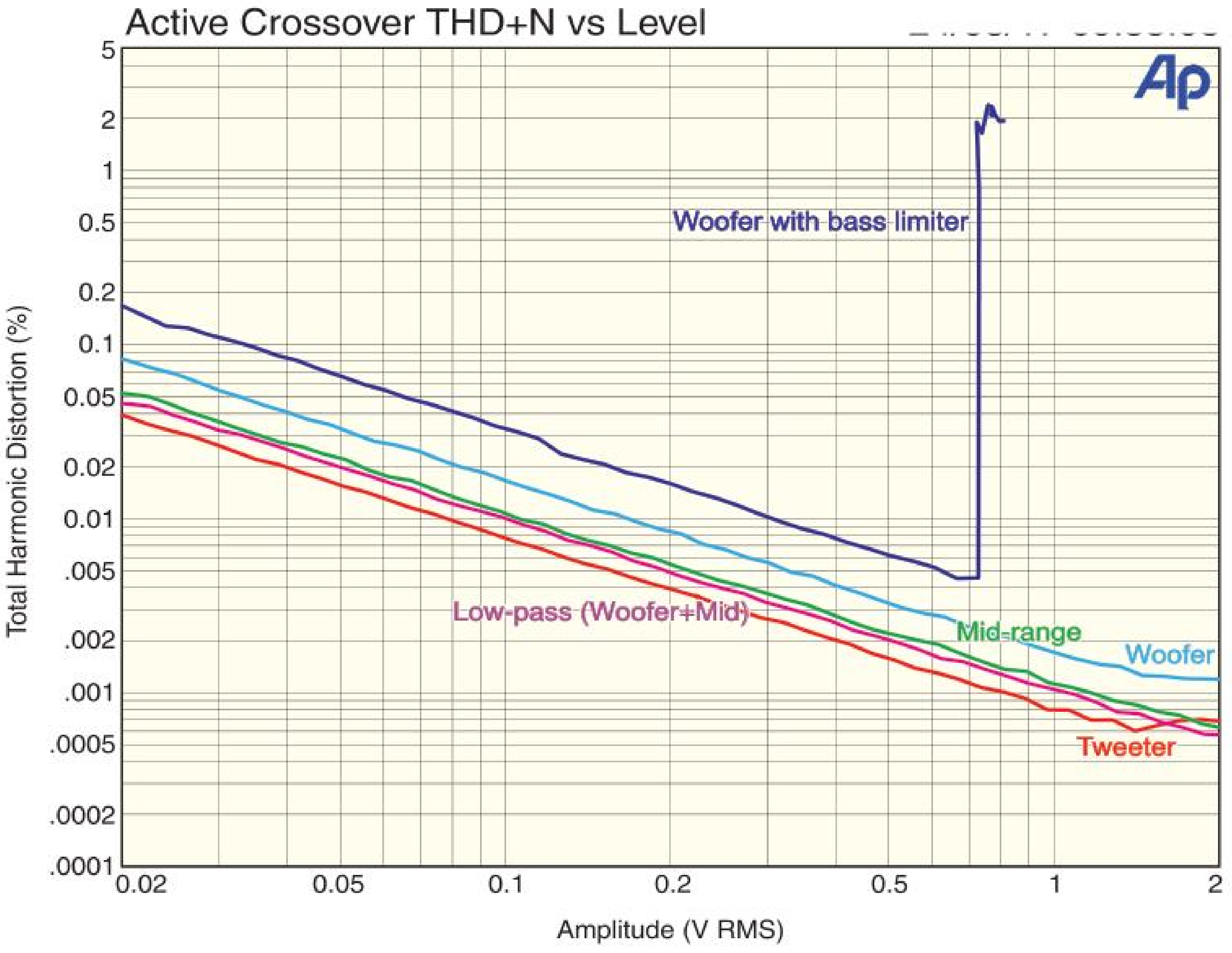


Fig.12: a plot of total harmonic distortion (actually THD + noise) against signal level for each output, demonstrating that almost all the distortion present is actually just noise. The dark blue curve demonstrates the operation of the bass limiter; the input signal was swept up to 2V with the unit set for unity gain. However, once the signal exceeds 0.72V RMS, the woofer output voltage barely rises further.

capacitor after soldering each one, as this can save a lot of time tracking down a short across the supplies later on.

The surface-mount resistors can now be now be soldered in place. These are coded with a 4-digit number: the first three digits representing the value and the last digit representing the number of extra zeroes. For example, a 1kΩ resistor (1000Ω) is labelled 1001: 100 plus one extra zero. For 100kΩ, (100,000Ω) the value is 100 with three extra zeroes. So it is labelled as 1003.

Install all the surface-mount resistors on the top and bottom of the PCB. The remaining surface-mount capacitors can now be fitted to the underside of the PCB.

Through-hole components

Once all the surface-mount components are installed, the through-hole components can be mounted.

Start with the resistors, but don't throw out all the lead off-cuts. The two inductors (L1 and L2) are simply wire links which pass through ferrite beads. Here's where you use a couple of those resistor lead off-cuts!

The diodes can now be mounted, taking care with orientation (the striped end is the cathode [K]).

Next, install the MKT polyester capacitors – there are 20 120nF and 20 22nF (their values should be clearly labelled). Electrolytic capacitors are mounted next. There are 35 in total – 25 are polarised and must be soldered in the right way around. The ten NP (non-polarised) 22µF capacitors can go in either way.

Potentiometers

Check that the pins on the potentiometers are all straight before insertion – if necessary, straighten them using flat-nose pliers. Double check that each pin has entered its hole before soldering in place.

The 8-ganged pots are best inserted by placing in the back row of leads first (ie, angle the potentiometer slightly) and then progressively insert the remaining pins as the pot is lowered onto the PCB.

Be careful with VR1, VR2 and VR7-VR10 as these have the same value (10kΩ) but VR1 is a log type (marked 'A'), while the remaining are linear (marked 'B').

VR11, the bass-limiter-threshold preset, is mounted with the screw adjustment to the left.

Power supply

Next to go in are the power supply components. All of these are polarised, so be careful with orientation.

First is the bridge rectifier, followed by the four filter capacitors (two 470µF and two 10µF), the Schottky diode and the two 15V regulators (again, note that they are different!). Both regulators should have their heatsinks attached via M3 screws and nuts before soldering in. Seat the regulators as far down on the PCB as their heatsinks will allow.

LED1 needs to mount with the correct orientation (longer lead is the anode). In order to allow it to poke through the front panel, it is bent over at 90°, 6mm back from the rear of the LED body.

Provision is made for a single 16VAC supply via CON4 or a 15V-0-15VAC supply via CON5. You will only need one of these. If using CON5 (a 3-way screw terminal) it is mounted with the opening toward the PCB edge.

LDR and LED pairs

LDR1/LED1 and LDR2/LED2 need to be made into two separate lightproof assemblies. Each assembly allows light from the LED to directly shine onto the face of an LDR.

We used 6mm-diameter black heatshrink tubing cut to 25mm in length to cover and secure the LED and LDR together and with a small bead of Blu-Tack (or similar) at the rear of each LED and LDR to prevent light entering from outside of the tubing. Orient the leads of the LED to the same plane as

Specifications

Measurement conditions:	**2V RMS in, 1.5V out, 20Hz-20kHz bandwidth**
Signal-to-noise ratio:	**100dB+ (100dB for tweeter, 105dB for midrange and 108dB for woofer)**
Frequency response, 20Hz-20kHz:	**+0,-0.25dB (see Fig.14)**
Total harmonic distortion plus noise:	**<0.002%, 20Hz-20kHz (see Fig.11)**
Distortion with bass limiter active:	**~0.005% before limiting; ~2% while limiting (see Fig.12)**
Output gain range:	**zero (full attenuation) up to 3.8 times gain**
Balance adjustment range:	**±7.5dB**
Bass/midrange crossover frequency (–6dB):	**85-900Hz (see Fig.18)**
Midrange/tweeter crossover frequency (–6dB):	**465Hz-5kHz (see Fig.17)**
Channel separation:	**>46dB, 20Hz-20kHz (see Fig.16)**
Input signal handling:	**up to 2.6V RMS**

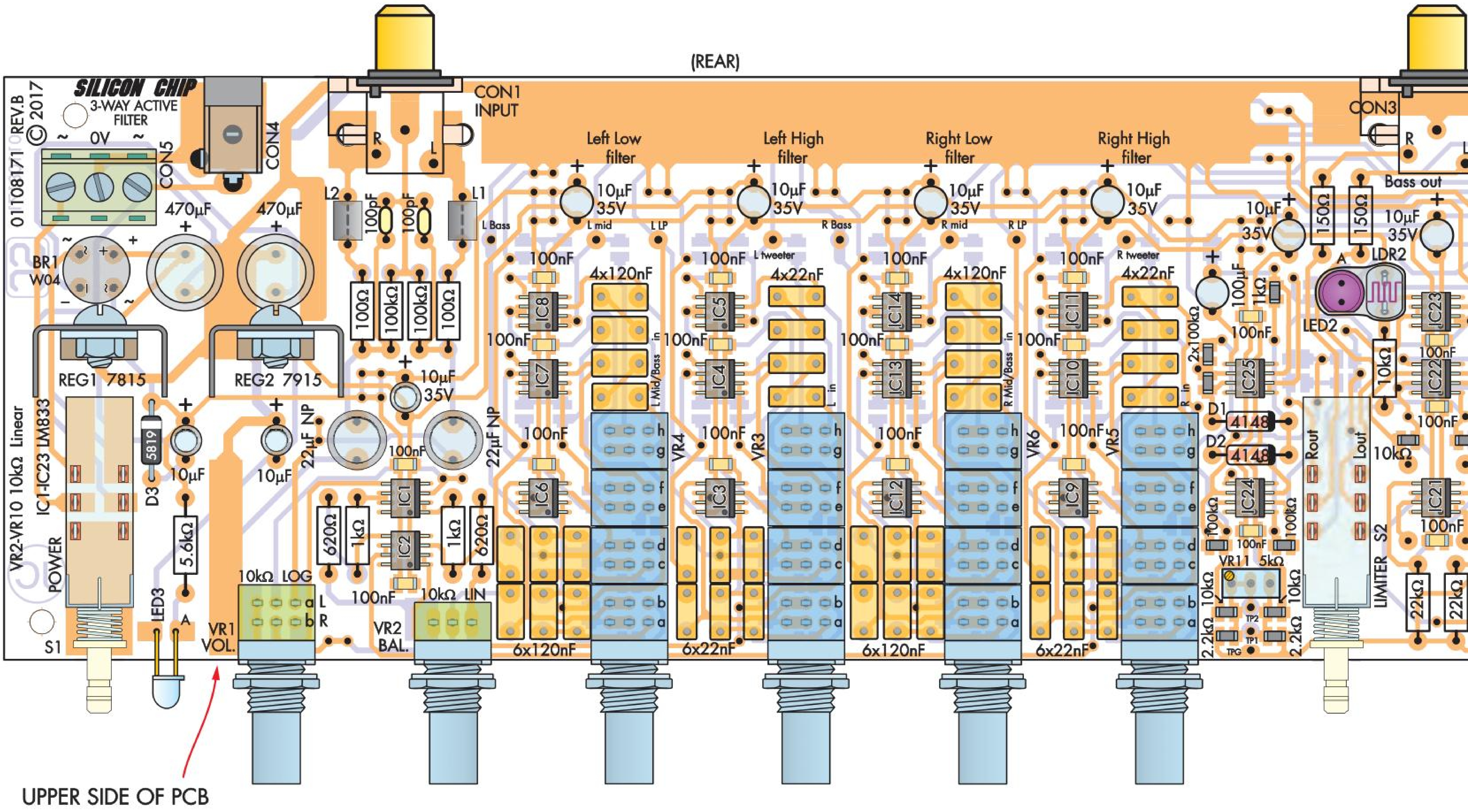
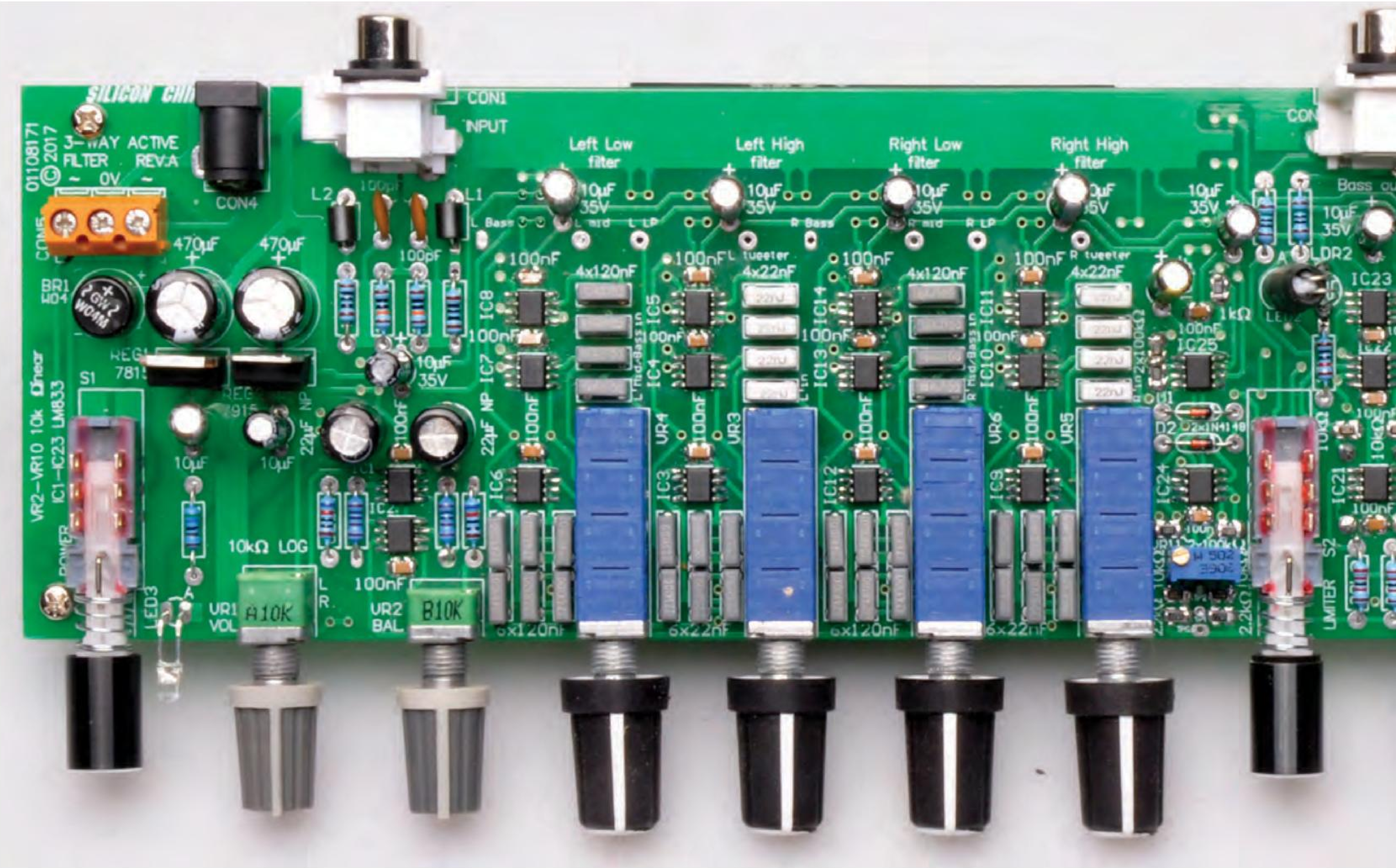
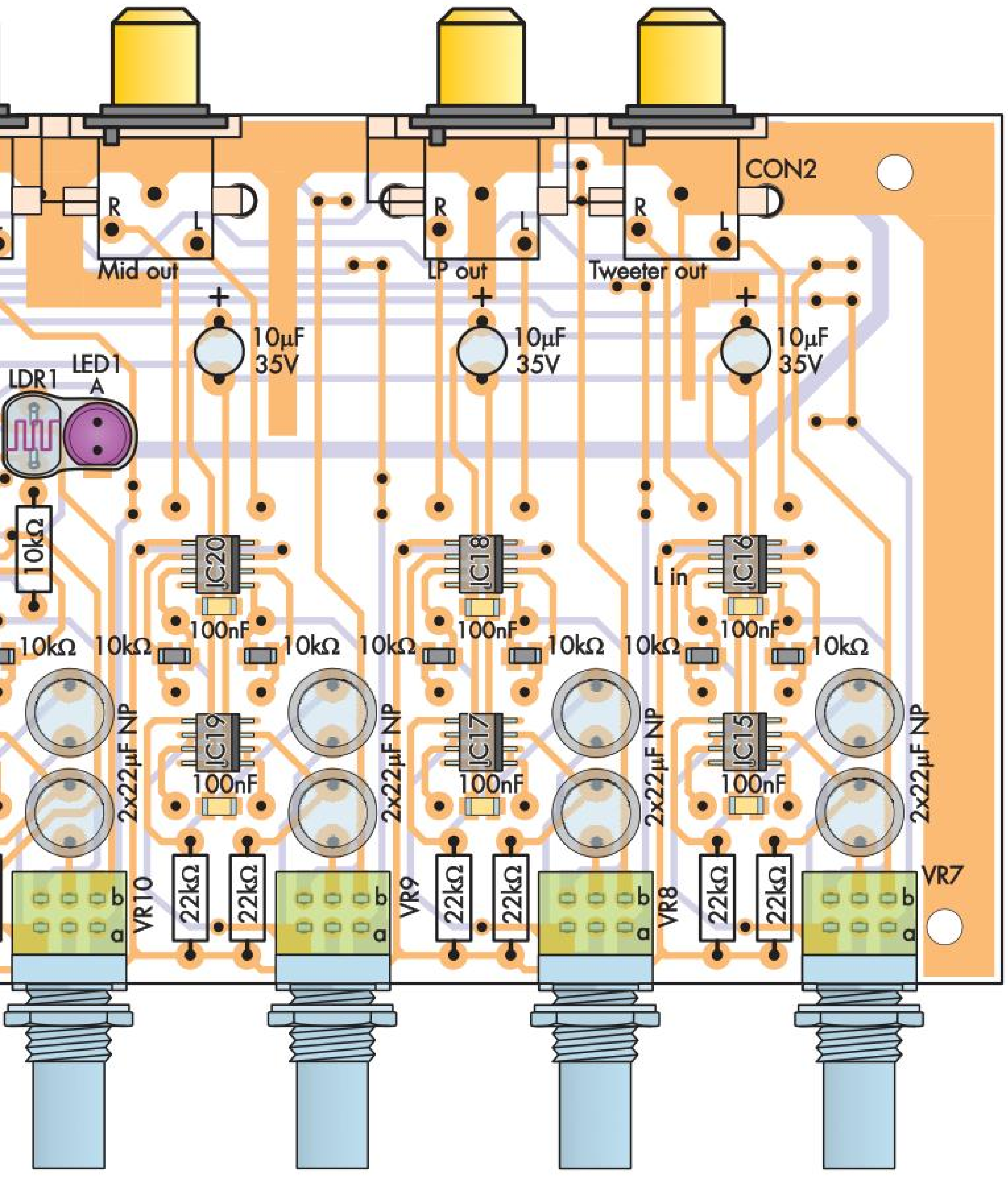

(REAR)
SILICON CHIP
3-WAY ACTIVE FILTER
01108171 REV.B © 2017
CON1 INPUT
CON3
CON4
CON5
Left Low filter
Left High filter
Right Low filter
Right High filter
Bass out
BR1 W04
470µF
REG1 7815
REG2 7915
22µF NP
10µF 35V
100nF
4x120nF
4x22nF
6x120nF
6x22nF
LDR2
LED2
D1 4148
D2 4148
VR11 5kΩ
Rout
Lout
LIMITER S2
VR2-VR10 10kΩ Linear
IC1-IC23 LM833
POWER
S1
LED3
5.6kΩ
5819
D3
10kΩ LOG
VR1 VOL.
10kΩ LIN
VR2 BAL.
VR3
VR4
VR5
VR6
620Ω
1kΩ
100Ω
100kΩ
100pF
L1
L2
UPPER SIDE OF PCB

Fig.13: most of the components mount on the top side of the PCB, although there are quite a few SMD resistors and a few capacitors mounted on the underside (see overleaf). Use this component layout diagram along with the same-size photo below to assist you in construction. The full parts list was printed in *Part 1* last month. The PCB is double sided, hence the number of apparently empty holes on the board which are 'vias' going through to the opposite side.

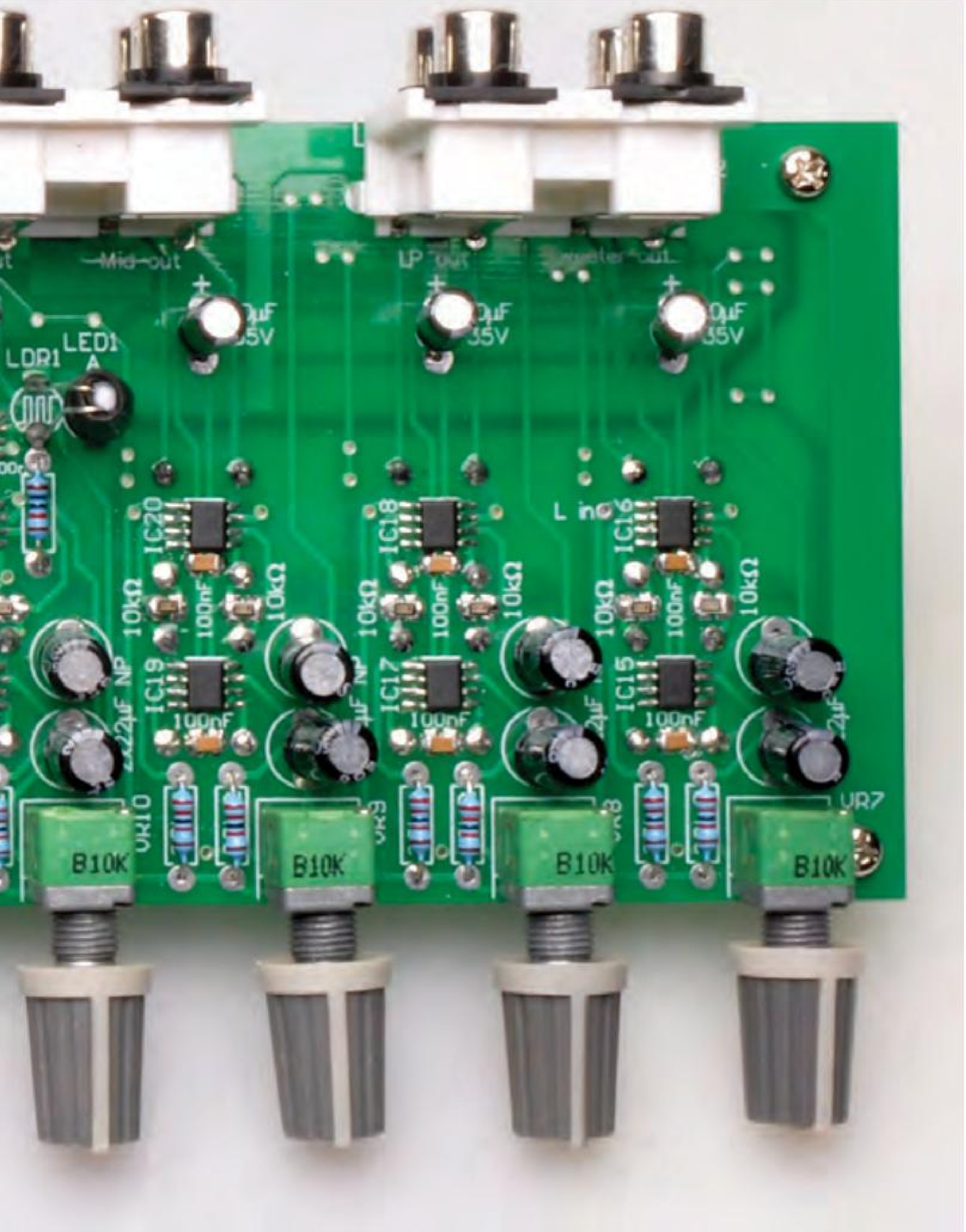


the LDR before shrinking the tubing with a hot air gun.

When installing onto the PCB, ensure that the LEDs are oriented correctly with the longer lead (the anode) inserted into the position marked 'A'. We inserted the LED directly onto the PCB, with the LDR leads bent over to insert into the LDR allocated holes. The LEDs are polarised but the LDR leads can be oriented either way in the PCB. (See the photo overleaf for more detail.) That completes the construction of the PCB, but before putting it in its case, we need to test it and set up VR11, the bass-limiter-threshold preset.



You'll need a very fine-tipped iron, a good magnifying glass and a steady hand to solder the SMDs.



Initial testing

Apply power (either 16VAC via CON4 or 15-0-15VAC via CON5) to test for voltage at the op amps. Switch on S1 and the power LED should light. Now measure voltage between pin 4 and pin 8 of one of the op amps.

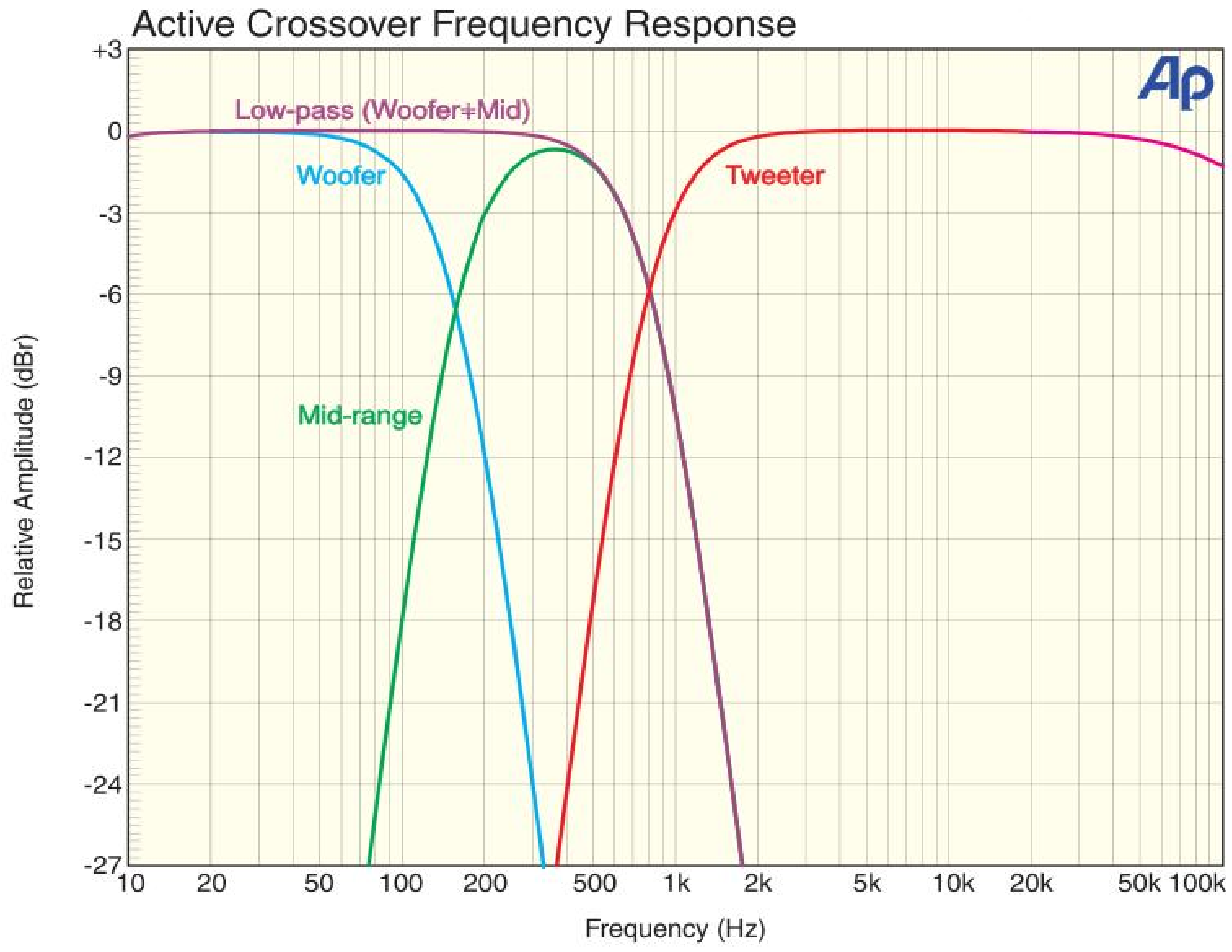


Fig.14: extended frequency response of each of the four outputs, showing that the –3dB points are well below 10Hz and above 100kHz respectively, making for a very flat summed response over the audible range (20Hz-20kHz). This demonstrates how the tweeter and low-pass outputs can be used as a two-way crossover, if necessary.

This should be close to 30V (ie, +15 to –15V). If this is not correct, switch off power and check construction for correct parts placement or for shorts on the power supply rails.

Setting it up

The input sockets can be connected either to the output of a preamplifier or directly to a line-level signal source such as a CD/DVD/Blu-ray player, MP3 player or mobile phone (thanks to the onboard volume control).

For driving a pair of 3-way loudspeakers, the woofer, mid-range and tweeter outputs should be connected to three stereo amplifiers, ie, one to power the woofers, one the mid-range drivers and one the tweeters. It's common practice to use lower power amplifiers for the mid-range drivers than woofers, and again for the tweeters compared to the mid-range drivers.

Note though, some (fairly unusual) program material may overload the amplifiers in such a configuration. Rock/pop music is normally safe in this sort of configuration as it is usually quite bass-heavy and so will overload the (larger) woofer amplifier first.

You will then need to determine the correct crossover frequencies, based on the specifications of your drivers and the cabinets they are mounted in and adjust the unit accordingly.

Making the adjustments

The easiest way to set the crossover frequencies is with an adjustable signal generator and AC millivoltmeter. You will need a signal generator that has a stable amplitude across a wide range of frequencies (eg, 30Hz to 10kHz or wider, if possible) and an AC millivoltmeter which can measure up to about 1V RMS and is accurate across the same frequency range.

If you don't have such tools, you could purchase them or alternatively, build our *Digital Audio Millivoltmeter* project from March 2011 and/or the *Touchscreen DDS Signal Generator* from the April 2018 issue.

Set the signal generator output to 30Hz and around 1V RMS and set all four level controls on the *Active Crossover* to maximum.

Hook up the signal generator to the inputs and the millivoltmeter across the centre pins of the two woofer outputs (we're assuming it has a battery or floating mains supply, ie, its ground is not earthed). Adjust the balance control until the millivoltmeter reads zero, indicating that the channels are correctly balanced.

Then connect the millivoltmeter normally to measure the left channel woofer output level. Adjust the volume control to get a reading of 1V RMS.

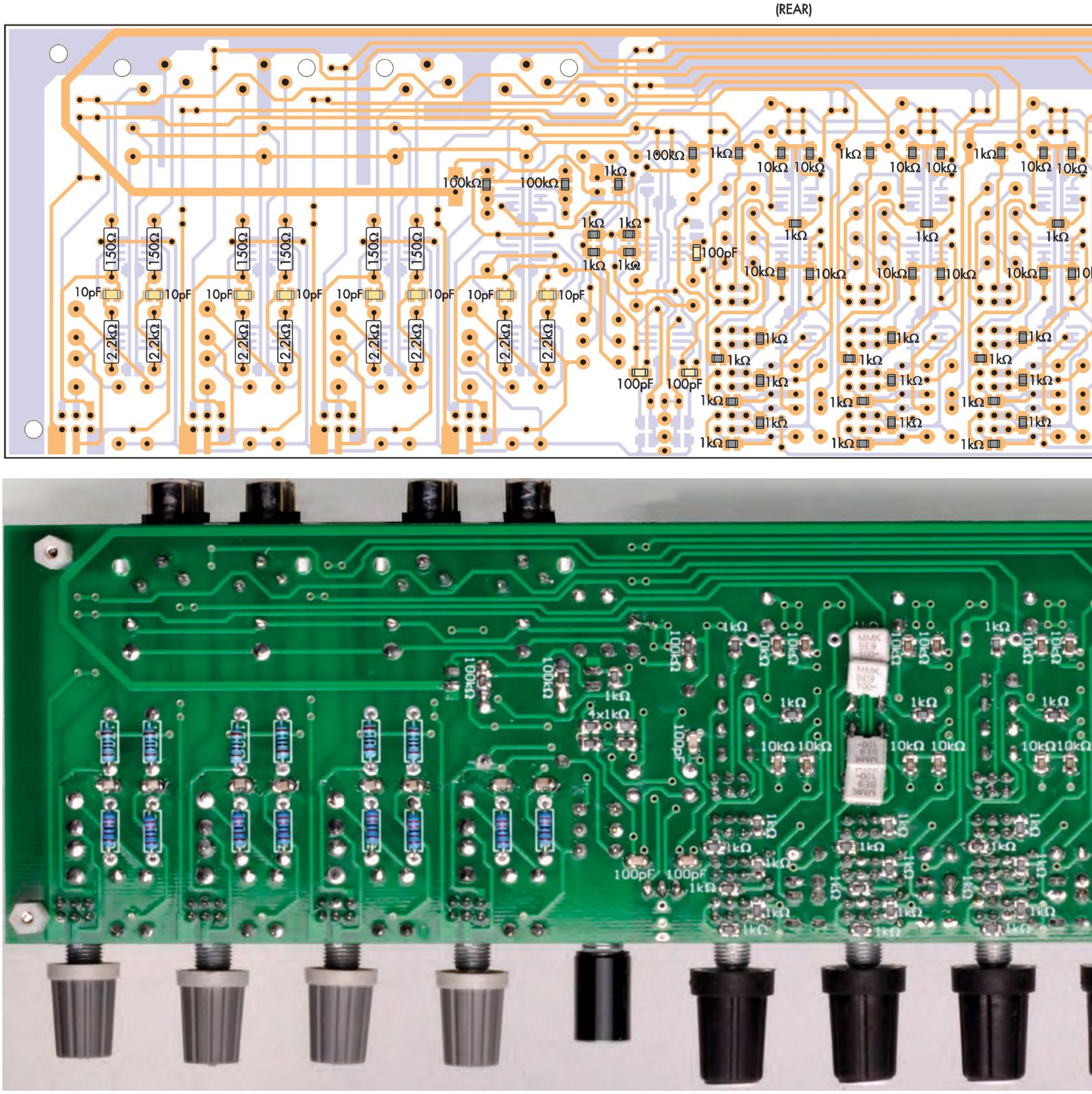

(REAR)
100kΩ
100kΩ
1kΩ
100kΩ
1kΩ
10kΩ 10kΩ
1kΩ
10kΩ 10kΩ
1kΩ
10kΩ 10kΩ
150Ω
150Ω
150Ω
150Ω
150Ω
150Ω
1kΩ 1kΩ
1kΩ 1kΩ
100pF
1kΩ
1kΩ
1kΩ
10kΩ
10kΩ
10kΩ
10kΩ
10kΩ
10pF
10pF
10pF
10pF
10pF
10pF
10pF
10pF
2.2kΩ
2.2kΩ
2.2kΩ
2.2kΩ
2.2kΩ
2.2kΩ
2.2kΩ
2.2kΩ
1kΩ
1kΩ
100pF 100pF
1kΩ
1kΩ
1kΩ
1kΩ
4x1kΩ
MMK

Fig.15: the component overlay and matching photo for the reverse (or under) side of the PCB shows the large number of SMD resistors and capacitors to be placed. The eight 100nF capacitors in the photo are only there because at the time, we'd run out of 120nF MKT capacitors (normally mounted on the top side of the board) Similarly, the diode shown tacked across the board in this prototype has been replaced with one mounted on the top side in the final version of the PCB.

Next, set your signal generator frequency to be your desired woofer/mid-range crossover frequency and then adjust the left channel lower crossover frequency potentiometer until you get a reading of 500mV RMS. This is 1V RMS minus 6dB.

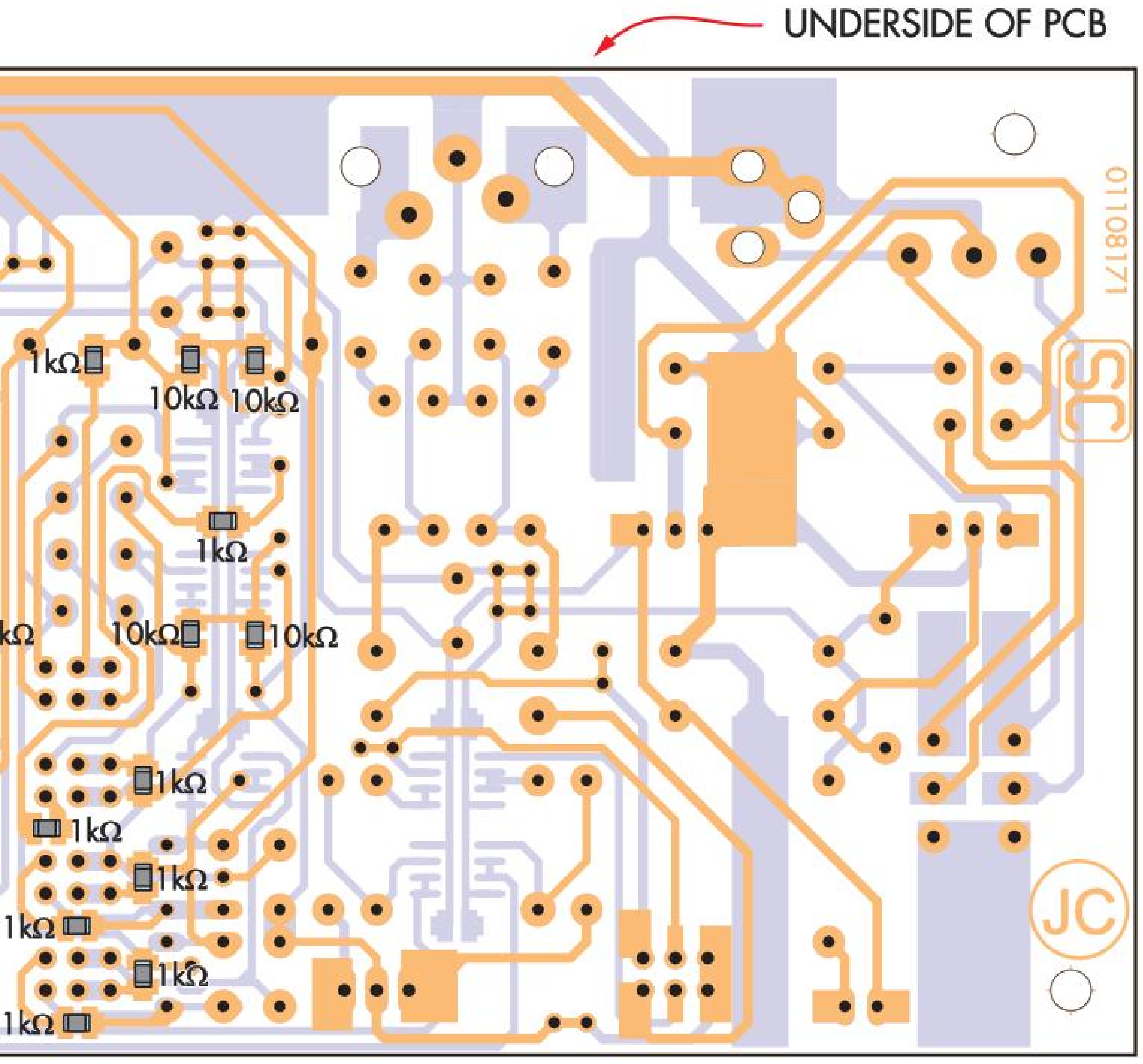
Then connect your millivoltmeter to the right channel woofer output and adjust the right channel lower crossover frequency to get the same result.

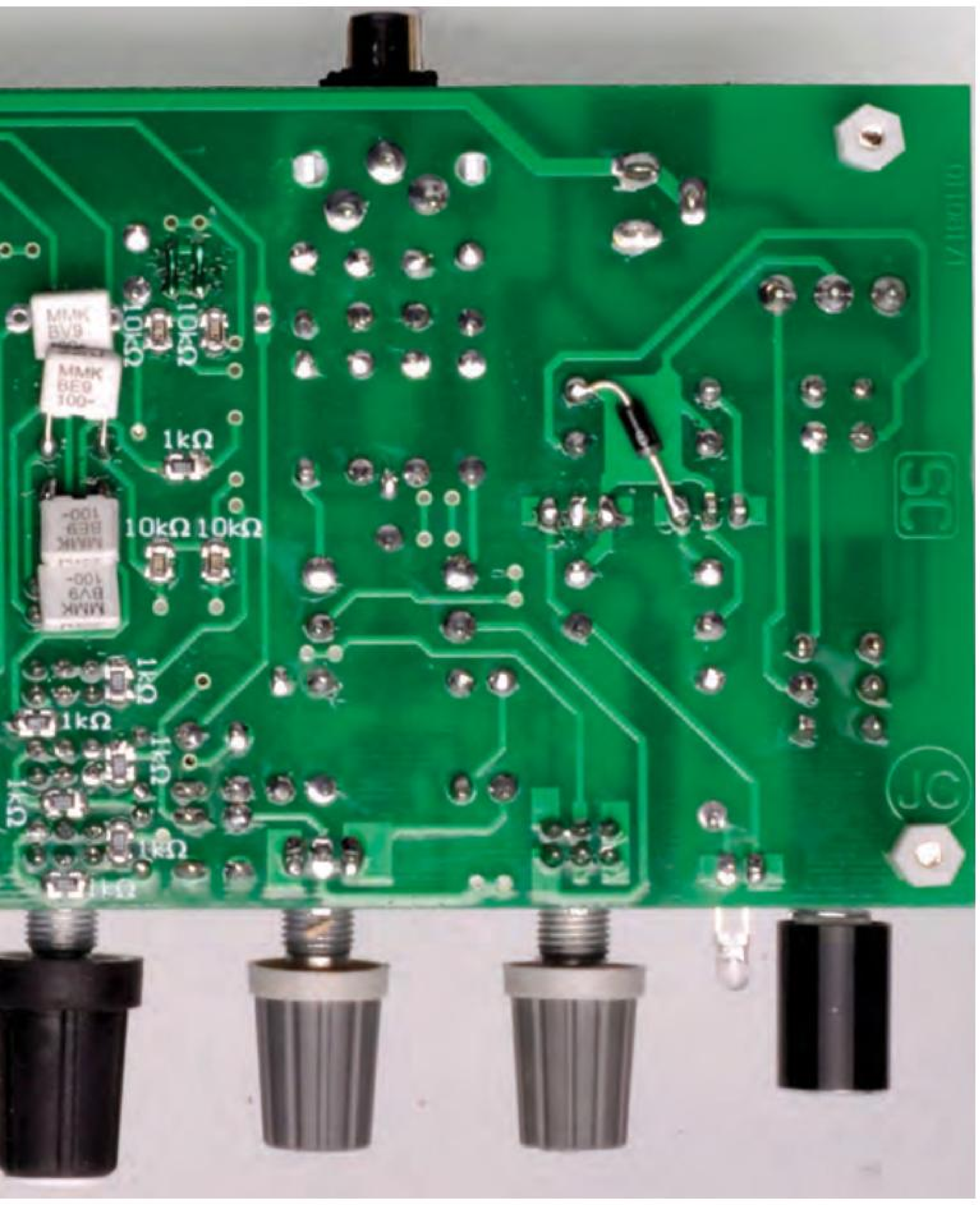
The procedure for adjusting the upper crossover threshold is the same, except that you start with a 10kHz signal and adjust the tweeter output level control to get 1V RMS, then set the signal frequency to your desired crossover frequency and adjust both upper crossover frequency adjustment pots until you read 500mV at both tweeter outputs.

You can then set the generator to a frequency in the middle of your mid-range band and adjust the midrange level output to get a reading of 1V RMS.

	Sensitivity	Impedance	Amplifier gain	Input level for 1dB(SPL)
Tweeter	96dB/W@1m	8Ω	10x (20dB)	-107dBV
Mid-range	89dB/W@1m	8Ω	15x (30dB)	-103.5dBV
Woofer	92dB/W@1m	4Ω	20x (40dB)	-112dBV

Table 1 – example of speaker system level adjustment





Adjusting the output level for each pair of drivers

At this point, you have set the crossover frequencies and the output amplitudes are all set to be identical, giving you a flat summed response. However, chances are your drivers do not have identical sensitivities.

Also, your individual amplifiers may not have the same gain. So you will need to change the relative levels of the outputs so that the drivers are producing identical sound levels at the crossover point(s).

Start by determining the sensitivities of each driver. These are normally specified by the manufacturer or supplier and are in units of decibels (sound pressure level) per watt at one metre (dB[SPL]/W @ 1m).

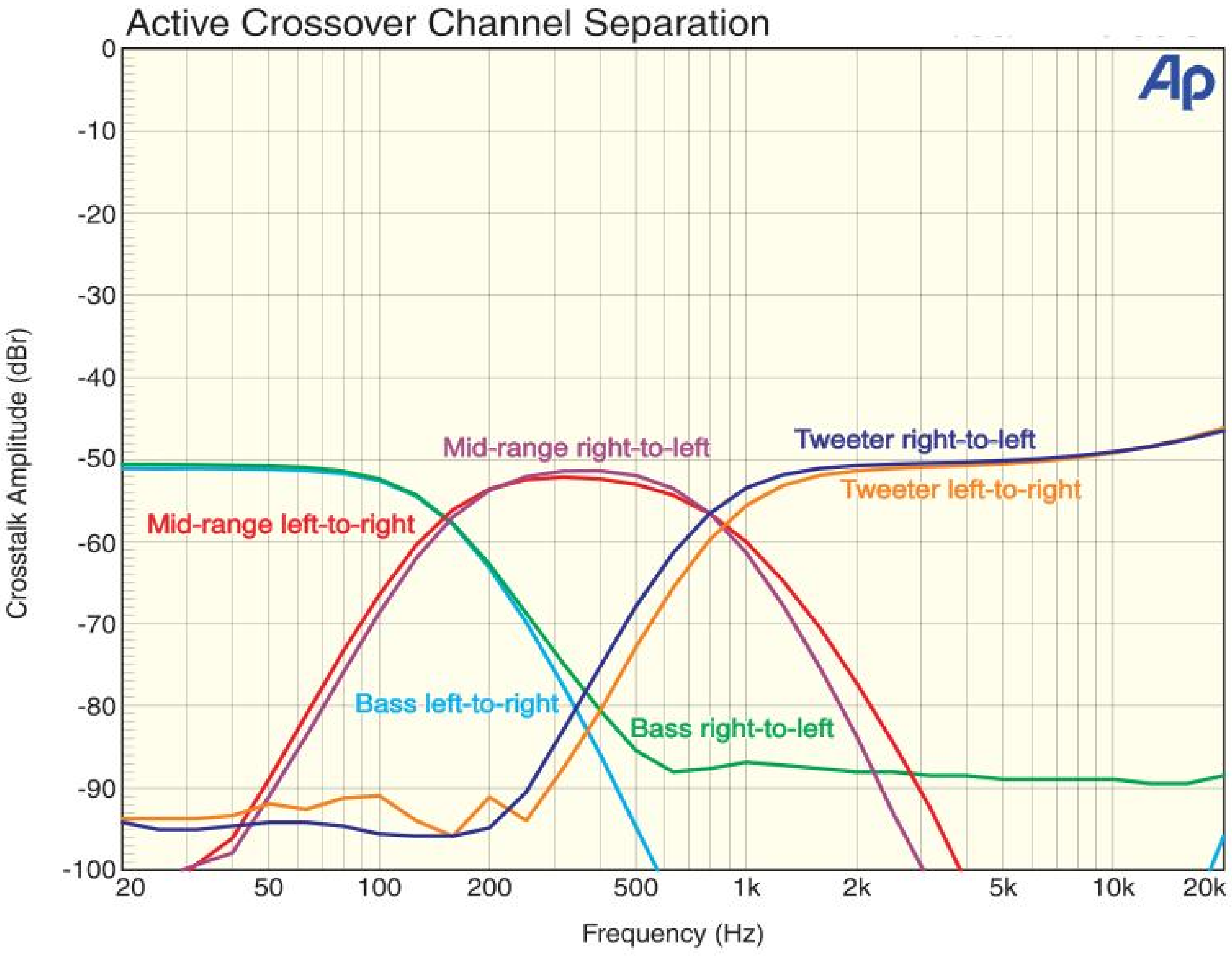


Fig.16: a plot of cross-talk between channels for the three primary outputs. As you would expect, cross-talk is highest within the frequency range that the output retains. Most of the cross-talk is due to the shared signal paths in the balance circuitry, with only a slight hint of capacitive cross-talk at higher frequencies (this effect is reduced at higher mid-range/tweeter crossover frequency settings).

In order to better explain the procedure, we'll use a hypothetical example of a three-way speaker system with drivers, as shown in Table 1.

In this example, each driver has a different sensitivity figure and the woofer's impedance is different from the other two. The stereo amplifiers used to drive each pair also have different gains, as indicated.

Impedance has an effect because this determines the signal amplitude required to deliver one watt to the driver. To determine the required voltage, take the square root of the impedance. So for a 4Ω driver, you need 2V RMS (P = V^2÷R); for an 8Ω driver, you need 2.828V RMS; and for a 6Ω driver, you need 2.45V RMS.

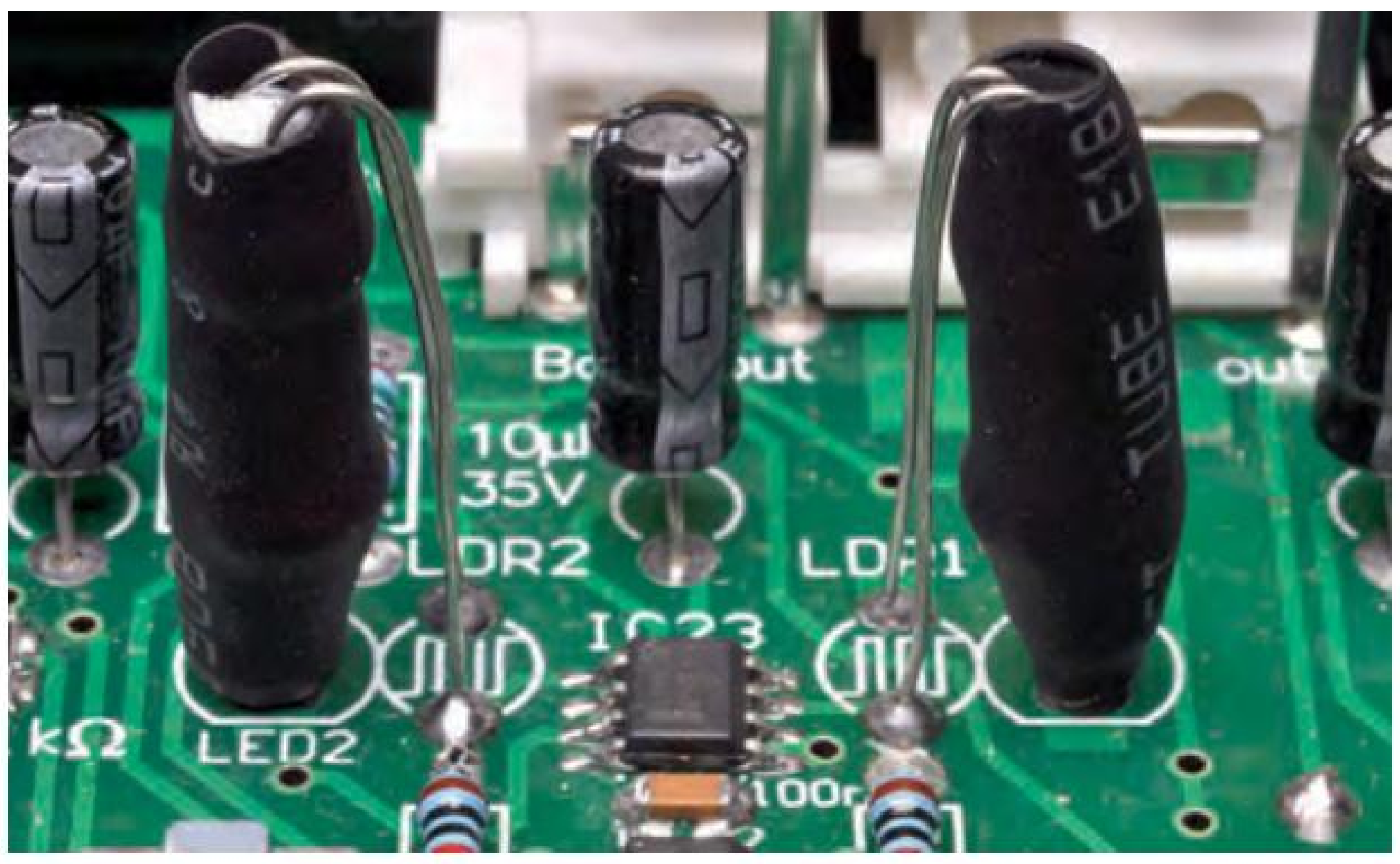
Now divide the required signal level by the amplifier gain to determine the signal that you need to feed into the amplifier to get 1W out of the driver. If you only have a dB gain figure, use the formula 10^(dB÷20) to determine the linear gain factor.

If your amplifier has a volume knob, the gain will depend on its setting; unless you plan on running it at maximum gain (and you already know what that is), you will have to feed a signal into the amplifier, measure the input and output amplitude and divide the output voltage by the input to determine the gain.

We suggest you do this before wiring up the outputs since otherwise it may be very loud and depending on the signal level you inject, you could damage the driver. This may result in a slightly higher reading (due to the outputs being unloaded) but the difference is unlikely to be significant.

So, in the case of our tweeter, we can compute the required amplifier input signal for 1W as 282.8mV RMS (2.828V÷10). For the mid-range driver, it's 188.6mV (2.828V ÷15) and for the woofer it's 100mV RMS (2V÷20).

Now we convert these figures to dB(V) using the formula dB(V) = 20log$_{10}$(VRMS). If your calculator doesn't have a base-10 log func-



This close-up shows the two LED/LDR assemblies, arranged so the light from the LEDs shines directly into their LDRs. Black heatshrink makes them lightproof.

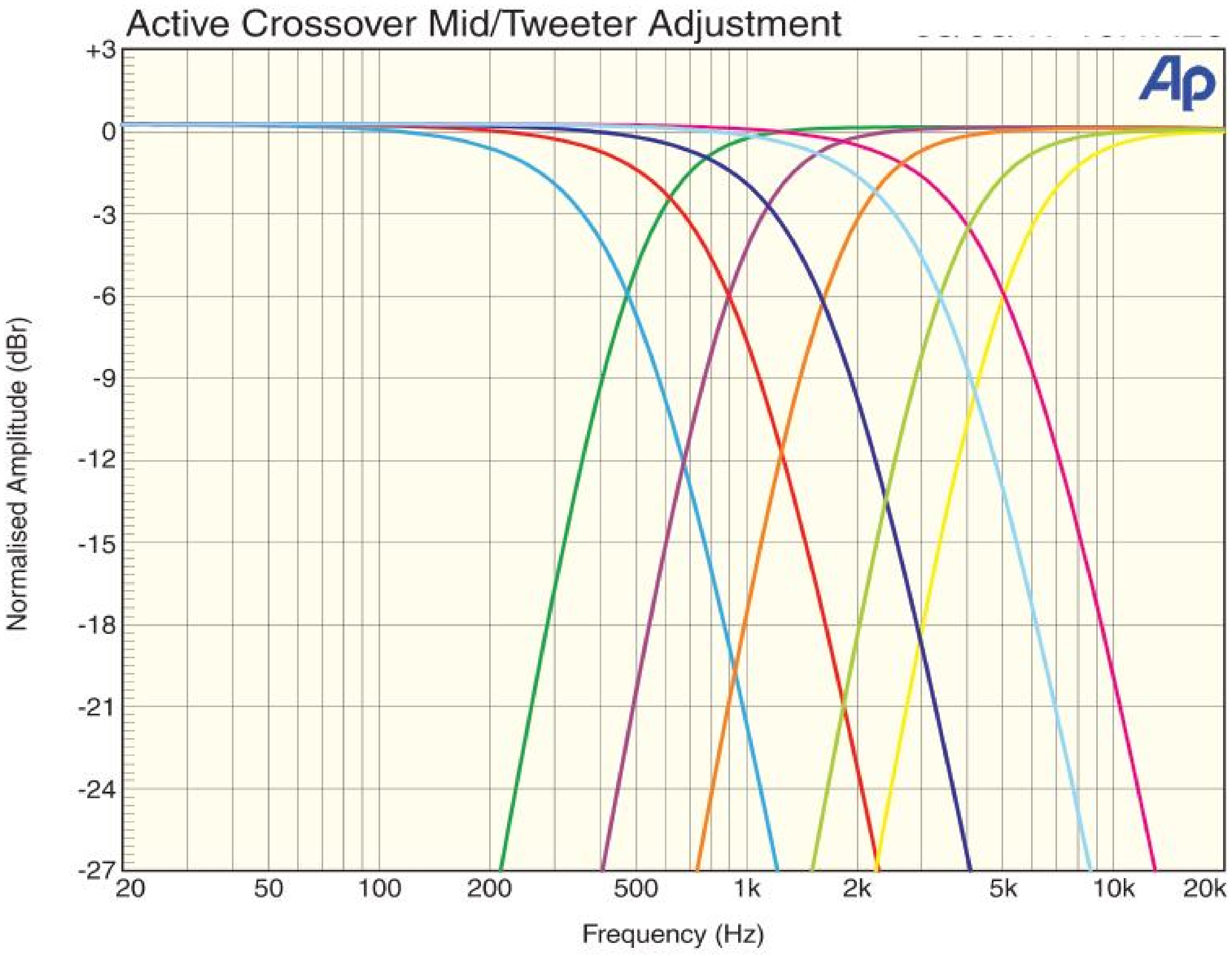


Fig.17: simultaneous frequency response plots of the woofer+mid and tweeter outputs with five different crossover frequency settings. This demonstrates the adjustment range and filter tracking and also shows how the unit can be used as a two-way crossover. In three-way mode, the effect is the same but the mid-range response will be hump-shaped, rather than extending all the way down to 20Hz.

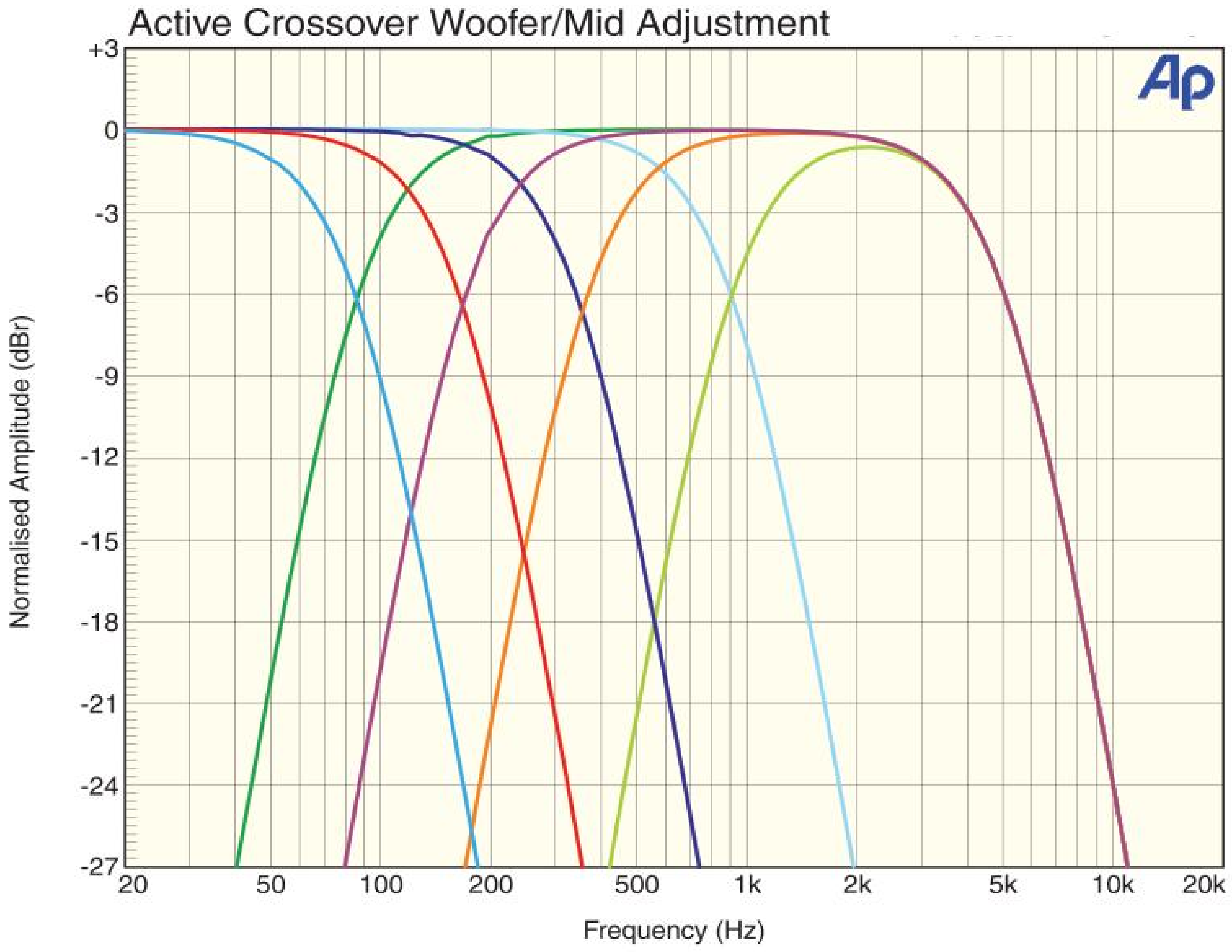


Fig.18: simultaneous frequency response plots of the woofer and mid-range outputs with four different crossover frequency settings. This demonstrates the adjustment range and filter tracking. With the woofer/mid crossover set to 900Hz, this is close enough to the mid/tweeter crossover frequency that the peak output level is below 0dB. Otherwise, it would produce a peak in the summed frequency response.

tion, you can take the base-e (natural) log and then divide by the natural log of 10, ie, $\log_{10}(x) = \log_e(x) \div \log_e(10)$.

This gives us figures of –11dBV for the tweeter, –14.5dBV for the mid-range driver and –20dBV for the woofer. Subtract the sensitivity figures from these values to get the required signal level to produce 1dB(SPL). These are shown in Table 1. This reveals that the mid-range driver requires the highest signal level, followed by the tweeter and then the woofer.

The first step to make the adjustments then is to set the output level for the mid-range driver to its maximum setting, feed a reference signal into the *Active Crossover* in the middle of the mid-range driver's frequency band (ie, between the two crossover points) and then adjust the input volume control until we get a reference level of 1V RMS at the mid-range output sockets.

Based on the figures we've just computed, we can determine that the tweeter output should be 3.5dB lower than this reference level.

Using the formula 10^(dBV÷20) we can determine that the tweeter output voltage needs to be adjusted to 10^(–3.5÷20) = 0.668V or 668mV. Using a similar procedure, inject a signal of the same amplitude as before but in the tweeter's frequency range (say, 10kHz) and then adjust the tweeter output to this level.

Similarly, we can compute the woofer output for the same amplitude input signal, at an appropriate frequency, should give an output of 10^(–8.5÷20) = 376mV RMS (–8.5 = [–112] – [–103.5]).

If you're using the unit as a two-way crossover, the procedure is essentially the same except that you set either the tweeter or low-pass (woofer+mid) output to 1V RMS and then adjust the other once you've computed the difference in level required.

Tweaking it

In a perfect world, the above procedure should give you a nearly flat response from your loudspeakers. However, there are a number of factors which can throw a spanner in the works.

For example, the fact that the drivers you purchase may not have exactly the sensitivity or frequency response the manufacturer specified. They may not even be identical to each other.

Then you also have effects of the enclosure on the performance of the drivers, the fact that their impedance will not be exactly the nominal value and will vary with frequency and so on.

All this means that that the setting you made above will only be approximately correct. It may well be good enough, but unless you make further measurements and do tweaking, you won't know if it can be improved upon.

The most scientific way to finish adjusting the *Active Crossover* to give the best results is using a device which can actually measure the frequency response of the loudspeaker, allowing you to calculate (or at least estimate) any further adjustments which need to be made to improve it.

You don't need particularly expensive equipment to do this. See the article titled *How to do your own loudspeaker measurements* (**www.siliconchip.com.au/Article/1248**), which describes how to use the low-cost *Champ* and *Prechamp* amplifier boards, with an electret microphone, a PC and a few other bits and pieces to measure loudspeaker frequency response.

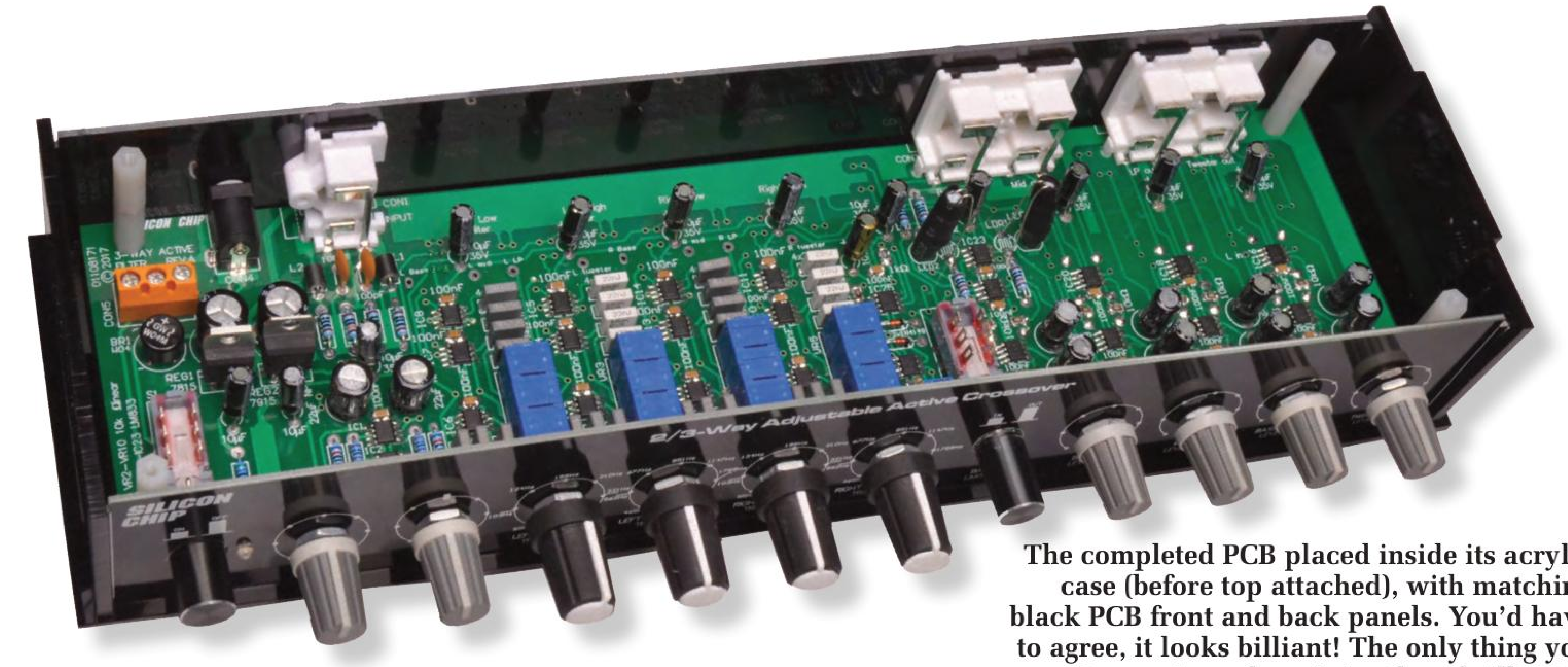
Assuming you go to the trouble of building such a rig, once you have measured the response, it's then just a matter of determining whether you need to slightly increase or decrease the level to one driver in order to even out the speaker's overall response.

If you do, you will normally notice a 'shelving' effect in the response curve. You can then re-measure to verify that your change is an improvement.

As we said earlier, various factors such as driver variances and enclosure design can also affect a driver's frequency response and thus you may find that there are dips or peaks near the crossover frequencies.

If so, this suggests that you may be able to flatten the response by adjusting the crossover frequency itself. You will need to make small adjustments and re-measure the loudspeaker to verify that your change led to an improvement (if not, reverse it). This is an iterative process and you may need to make a number of adjustments before you are happy with the overall response.

If you don't have the equipment to do this and you have well-calibrated ears and a good variety of source material, which you are familiar with (ideally, having listened to it multiple times on speakers or headphones with a flat



The completed PCB placed inside its acrylic case (before top attached), with matching black PCB front and back panels. You'd have to agree, it looks billiant! The only thing you can't experience here is just how brilliant it makes your speakers sound – and you'll have to build it to hear that!

response), you might trust yourself to tweak the crossover 'by ear'. However, there is no guarantee that you will get the best result with this method.

Limiter adjustment

The signal level at which the bass limiter becomes active (when it is switched on via S3) can be adjusted using trimpot VR11.

Typically, you would set the limiter to restrict the signal level so that the amplifier/woofer combination you are using does not run into clipping. The signal level at which clipping occurs depends on the amplifier power rating, its gain, the woofer power rating and its impedance. So you will need to calculate the signal level at which clipping will occur to set the limiter correctly. You could adjust it experimentally; however, you risk causing damage using that method.

Briefly, take the lower of the two power ratings (amplifier or woofer, taking into account the woofer's nominal impedance) and then calculate the RMS voltage required to be delivered to the woofer's impedance to achieve that power level using the formula $V = \sqrt{P \times R}$. Then divide this by the amplifier's gain to determine the maximum signal level at the amplifier's input. You can then multiply this RMS voltage by 1.414 ($\sqrt{2}$) to calculate the maximum peak signal voltage before clipping occurs.

The limiter level can be monitored between TPG and TP1 for the positive peak level and TPG and TP2 for the negative level. You should get a similar reading in both cases (with opposite polarity). Adjust VR11 until the voltages at TP1 and TP2 are just below the peak voltage level you computed above.

Acrylic case

The case is formed from four pieces which slot together, forming the top, bottom and ends. The front and back of the case are high-gloss, screen printed PCBs with drilled holes for the controls, connectors and LED.

The whole lot is held together with eight screws and twelve tapped spacers, along with tabs and slots joining the panels to each other.

The first step is to loosely fit the front and rear panels to the main PCB. The rear panel slips on over the 10 RCA connectors and is held in place with three short black 4GA self-tapping screws which go into the middle of the two 4-way RCA sockets and to the side of the 2-way RCA socket.

Before fitting the front panel, you need to remove the nuts and washers from all of the potentiometers. It's then just a matter of slipping the panel over the pot shafts and loosely re-attaching the washers and nuts while guiding LED1 into its hole.

Now remove the protective film from the base panel. This is the largest acrylic panel, with two extra slots compared to the top. Do this carefully since the two long slots are near the edges of the panel, making it relatively weak – don't hold it by these edges or press on them.

You can orient the acrylic panels so that the outside (visible) faces are either matte or gloss black; we prefer matte, since it gives better resistance to fingerprints and hides scratches.

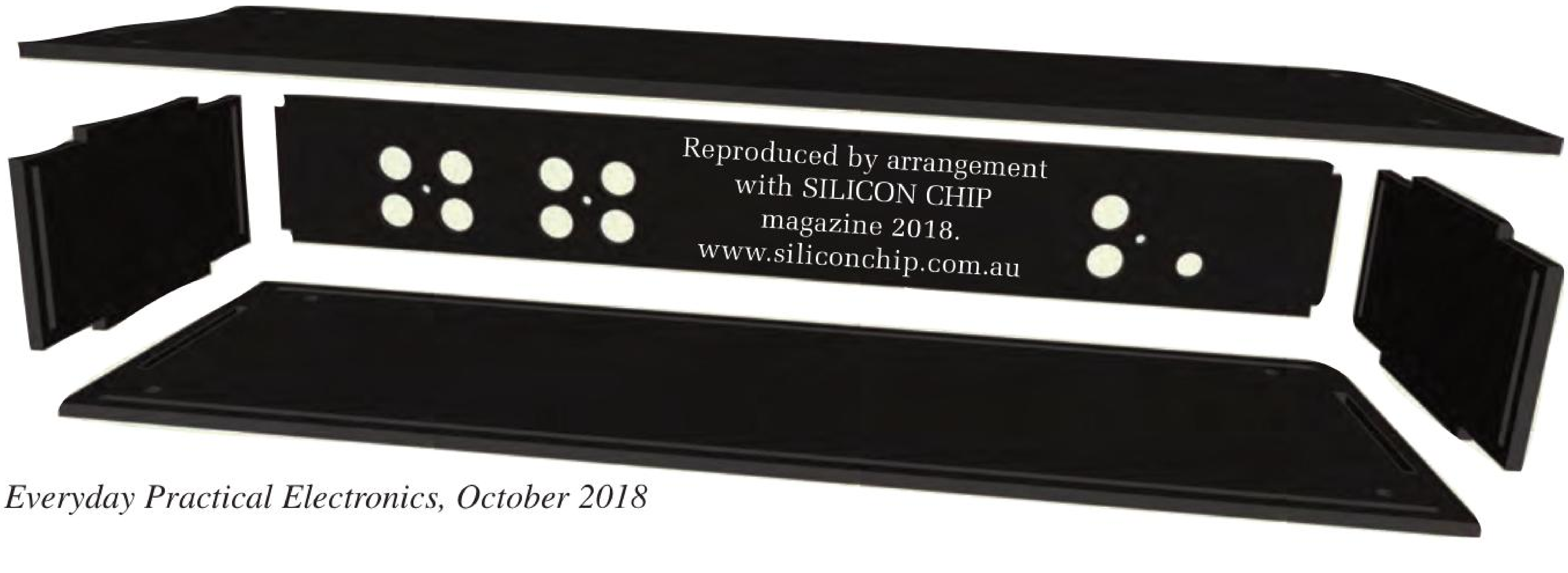
Feed the four 32mm machine screws up through the bottom and screw a 9mm tapped nylon spacer onto each shaft until the screw is held firmly in place.

Now remove the protective coating from the two side panels and push it onto the sides of the front and rear panels, so that the tabs in those panels go through the slots on the side panels.

You can then lower the PCB onto the bottom panel, lining up the screws with its mounting holes. Screw four 15mm M3 spacers fully onto the screw shafts to hold the PCB in place, then screw the other four 15mm spacers on top.

Now you can remove the protective coating from the top panel and lower it into place. You may need to cajole the front and rear panels to fit into the slots.

Use four black M3 × 8mm machine screws to attach it to the top of the four spacers, then tighten up all the potentiometer nuts and push the knobs onto the pot shafts. Stick on some rubber feet and the case is complete.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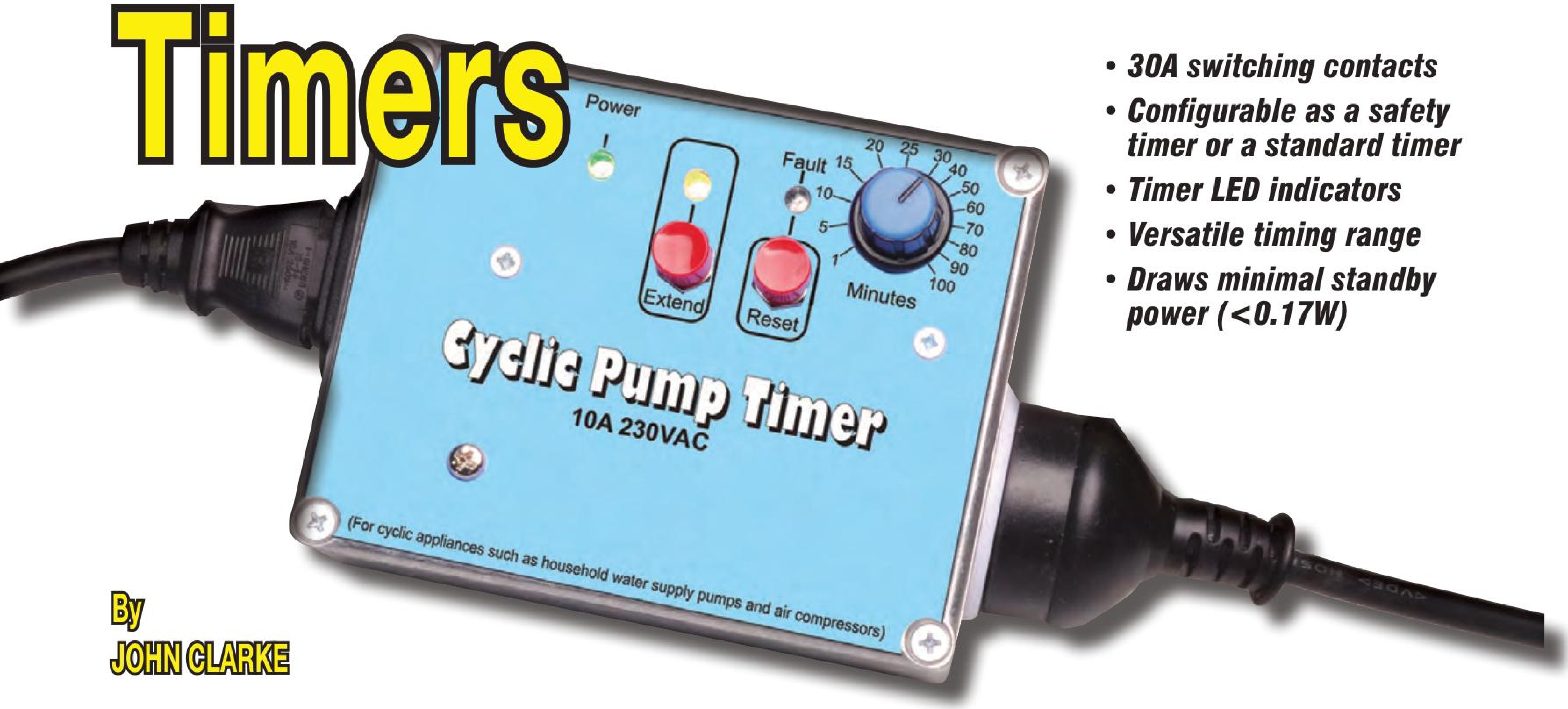
Exploded view of the laser-cut acrylic case designed for the *Active Crossover*.

Two 230VAC Mains Timers



- ***30A switching contacts***
- ***Configurable as a safety timer or a standard timer***
- ***Timer LED indicators***
- ***Versatile timing range***
- ***Draws minimal standby power (<0.17W)***

By
JOHN CLARKE

Do you have a pump or compressor which runs cyclically? Then you don't want it to keep running if a pipe bursts, do you? To stop that happening, build ths *230VAC Cyclic Pump Timer*. Or perhaps you have an appliance which you want to run for a set time and then turn off. For that you need to build a *230VAC Period Timer*. It can be set to run for any period up to 250 minutes and then it will turn off.

The initial impetus for these timer projects came from a reader's suggestion. He had a pump which supplied water to his house on a farm. One day the pipe from the pump to the house burst and then the pump completely drained his rain-water tanks.

And coincidentally, he also had an air compressor which again had burst a hose, so the compressor ran for the entire weekend!

In both of these situations, the result could have been even worse if the pump had failed from running dry or the compressor motor had burnt out because of overheating.

After all, most pumps and compressors are not usually rated for continuous operation. Both of these situations could have been avoided with a suitable timer. Mind you, the total draining of water storage on a farm could also happen if a tap was inadvertently left on.

So that was how the *Cyclic Pump Timer* came to be designed. It monitors when power is being used and if it runs for more than the usual cycle, for example 10 minutes, its internal heavy duty relay will switch off the power.

When it switches off the power, it lights a red LED which tells you a fault condition has occurred.

You can restore operation by hitting the Reset button and then determine where the fault lies.

Version 2 – Period Timer

During the design process we realised that the proposed circuit had a wider

Specifications

***Input** 230VAC 10A*
***Power consumption**............ Less than 0.17W with relay off, less than 1.33W with relay on*
***Time-out adjustment**......... 1-100 minutes (Cyclic Pump Timer) or 2.5-250 minutes (Period Timer)*
***Cyclic Pump thresholds**..... Above 700mA AC (approximately 160W for a resistive load) for timer start, below 250mA AC for timer reset (around 60W)*

IMPORTANT – Warning!

This project is only for those who have the experience and knowledge to work with mains electricity – it is ***NOT*** suitable for unsupervised beginners.

Furthermore, this project was originally designed for Australian constructors, and while Australian mains and associated standards are largely compatible with the UK, Australia use a different mains outlet socket/plug. UK constructors will need to use a suitably rated UK mains outlet, which may require the use of a larger box.

Parts list
Cyclic 230VAC Timer

- 1 double-sided PCB, available from the *EPE PCB Service*, coded 10108161, 85 × 78mm
- 1 double-sided PCB, available from the *EPE PCB Service*, coded 10108162, 83 × 35.5mm
- 1 diecast box, 119 × 94 × 57mm
- 1 panel label, measuring 119 × 94mm
- 1 UK standard mains socket
- 1 IEC panel connector with fuse holder
- 1 UK standard 230VAC 13A mains plug to IEC socket lead
- 1 10A slow-blow M205 fuse (F1)
- 1 30A SPDT 12V relay (Altronics S 4211) (RLY1)
- 1 4.7μH axial inductor (L1)
- 1 10-way box header and matching IDC plug (CON3)
- 1 PCB-mounting 10-way IDC 'transition plug' header (CON4)
- 1 Vigortronix VTX-214-003-112 12V 3W AC-to-DC converter (REG1) (element14 # 2401035)
- 1 AC1015 Talema 15A current transformer (RS Stock No. 537-4508) *
- 1 S14K275 MOV (MOV1)
- 1 3-way screw terminal with 5.08mm spacing (CON1)
- 1 2-way screw terminal with 5.08mm spacing (CON2)
- 2 SPST momentary pushbutton switches (S1,S2)
- 1 16mm 10kΩ linear pot with knob to suit (VR1)
- 1 DIL-8 IC socket
- 1 90mm length of 10-way ribbon cable
- 4 rubber feet
- 2 5.3mm crimp eyelets (yellow insulated)
- 7 M3 tapped × 9mm nylon spacers
- 16 M3 × 6mm machine screws (or 7 M3 × 6mm countersunk screws and 9 M3 × 6mm machine screws) (for PCB and relay mounting)
- 2 M3 × 10mm countersunk or machine head screws (for IEC mounting)
- 2 M4 × 12mm countersunk or machine screws (securing earth eyelets)
- 4 M3 nuts
- 2 3mm inner diameter star washers (under IEC connector nuts)
- 2 M4 nuts with star washers
- 1 20mm length of 3mm diameter heatshrink tubing (relay coil terminals)
- 1 50mm length of 6mm diameter heatshrink tubing
- 1 250mm length of 10A three-core mains cable (for Neutral blue wire, Live brown wire and Earth green/yellow wire)
- 1 60mm length of 0.7mm diameter tinned copper wire
- 9 PC stakes
- 7 100mm long cable ties

Semiconductors
- 1 PIC12F675-I/P programmed with 1010816A.hex (IC1)
- 1 LM2936-5.0 ultra-low quiescent current 5V regulator (REG2)
- 1 BC337 NPN transistor (Q1)
- 4 1N4148 diodes (D1-D4) *
- 1 1N4004 1A diode (D5)
- 1 4.7V 1W zener diode (ZD1) *
- 1 5mm high intensity green LED (LED1)
- 1 5mm high intensity yellow LED (LED2 in Fig.1)
- 1 5mm high intensity red LED (LED3 in Fig.1 or LED2 in Fig.2)

Capacitors
- 1 47μF 16V PC electrolytic
- 4 10μF 16V PC electrolytic [3 only for version 2]
- 2 100nF MKT polyester (63 or 100VDC)
- 1 100nF X2 class metallised polypropylene

*not required for version 2

Resistors (0.25W, 1%)

1 100kΩ	2 10kΩ [1 only for version 2]
1 2.2kΩ	4 1kΩ [3 only for version 2]

application, as a general purpose timer, but without the current monitoring facility.

So that became version 2, a straight 230VAC timer. This could be used for any device that you might turn on and then you might forget to turn it off after you used it. So it could run for many hours or even days which would be completely undesirable. Not only does it create a fire risk, it would also chew through power, costing you real money.

With this *Period Timer*, you could set a reasonable time when you turn on a soldering iron, an electric iron or a battery charger etc, without its own cut-out.

We are sure you'll think of lots of other applications.

Both versions of the timer use the same PCBs and both are housed in a small diecast case with an IEC mains connector and fuse for the power input at one end and a 250VAC mains outlet at the other end of the box.

On the lid are two pushbutton switches, a knob to set the operating period and two or three LED indicators. Their functions vary in each version of the timer.

Time period

The *230VAC Cyclic Pump Timer's* period can be varied from 1 to 100 minutes, while the *230VAC Timer* (for appliances) can be set from 2.5 to 250 minutes (a little over four hours).

Now let's have a look at the circuit which is shown in Fig.1 overleaf. This includes all the circuitry for version 1.

To build the simpler *230VAC Period Timer*, you leave out all the components associated with the current transformer, in the green shaded section of the circuit and one of the LED indicators.

The circuit

So now we will discuss the full circuit which is controlled by a PIC12F675 microprocessor. For simplicity, we'll assume the timer is being used with a pump (for a compressor and any other cyclical device, operation is identical).

All the 230VAC mains circuitry is shown on the righthand side of the circuit, highlighted in pink.

The mains supply comes in via an IEC male connector. The live line from the 230VAC mains passes through the core of the current transformer (T1), effectively a single-turn primary, and then through the contacts of a 30A relay (RLY1). This in turn connects to the live (L) terminal of the 3-pin mains output socket.

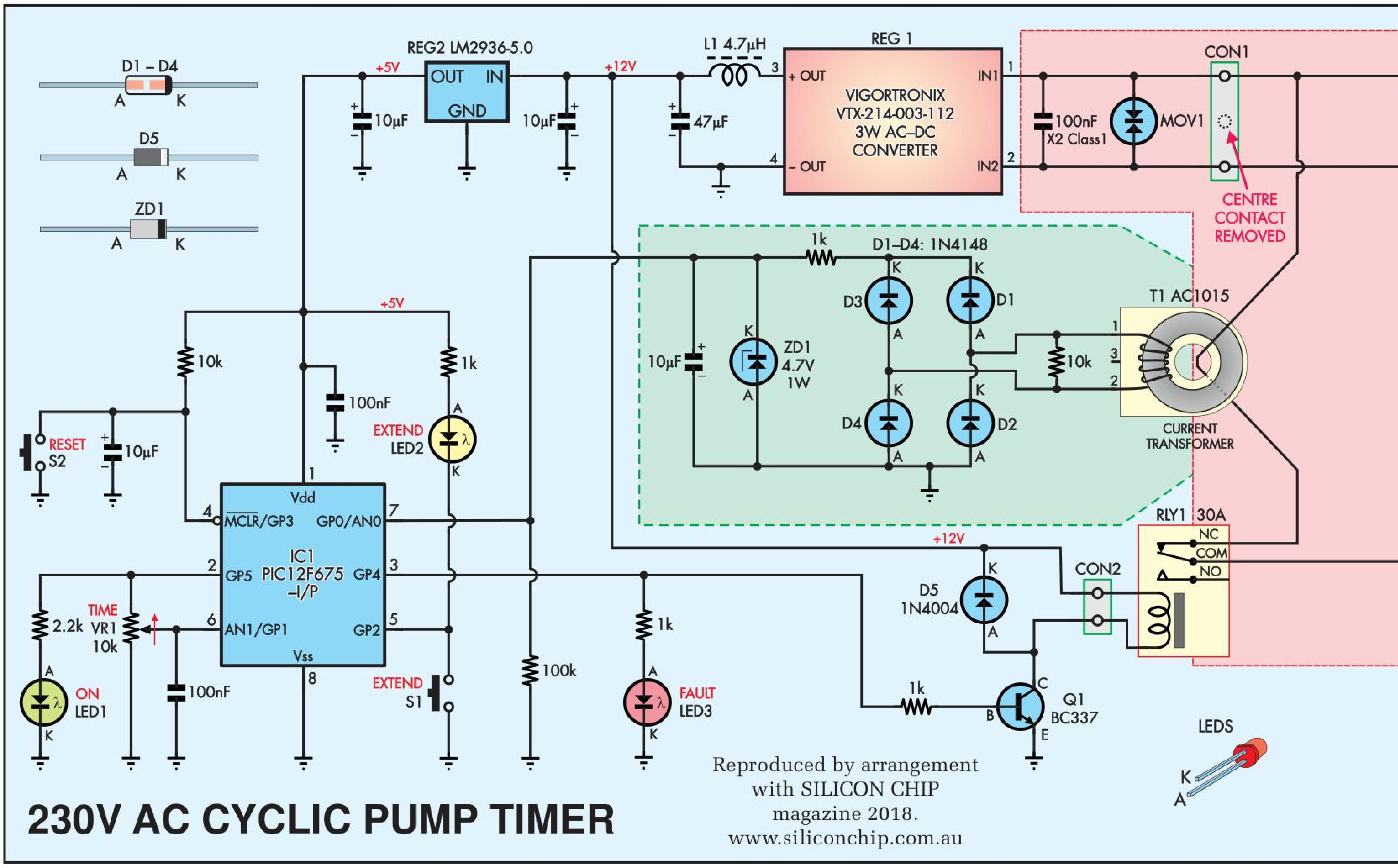
The secondary winding of current transformer T1 drives a bridge rectifier (diodes D1 to D4). The rectified output is fed via a 1kΩ resistor to a 4.7V zener diode, which limits the maximum DC level, and is then filtered by a 10μF capacitor and connected to the AN0 input (pin 7) of the PIC12675F.

If there is no current passing in the primary of transformer T1 (ie, the pump is not turned on), it produces no voltage at its secondary. But if the current exceeds 700mA, the resulting voltage of about 1V, detected at pin 7 of IC1, tells the PIC the pump has started running.

It then starts its timer function, having first read the voltage at the AN1 input, pin 6. This input monitors the wiper of potentiometer VR1, which is the timer control.

VR1 can be adjusted between 0V and 5V, giving a time of one to 100 minutes, as mentioned earlier.

With the pump running, green LED1 will be flashing to indicate the timer is functioning. If the pump operates normally, the timer function will be stopped when the voltage at pin 7 drops to zero, indicating that pumping has stopped. LED1 will stop flashing and be on continuously.


D1 – D4
A
K
D5
A
K
ZD1
A
K
REG2 LM2936-5.0
+5V
OUT
IN
GND
10μF
10μF
+12V
L1 4.7μH
47μF
REG 1
+ OUT
– OUT
IN1
IN2
VIGORTRONIX
VTX-214-003-112
3W AC–DC
CONVERTER
100nF
X2 Class1
MOV1
CON1
CENTRE
CONTACT
REMOVED
1k
D1–D4: 1N4148
D3
D1
D4
D2
10μF
ZD1
4.7V
1W
10k
T1 AC1015
CURRENT
TRANSFORMER
+5V
10k
1k
100nF
EXTEND
LED2
RESET
S2
10μF
Vdd
MCLR/GP3
GP0/AN0
IC1
PIC12F675
–I/P
GP5
GP4
AN1/GP1
GP2
Vss
2.2k
TIME
VR1
10k
ON
LED1
100nF
EXTEND
S1
100k
1k
FAULT
LED3
RLY1 30A
NC
COM
NO
+12V
CON2
D5
1N4004
1k
Q1
BC337
B
C
E
LEDS
K
A

230V AC CYCLIC PUMP TIMER

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Fig.1: the circuit for version 1, the *Cyclic Pump Timer*. The current through T1 when the pump or compressor is in operation produces a voltage in its secondary which is sensed by the PIC. Power is cut if this voltage goes on for too long.

On the other hand, if the pump continues to run and exceeds the period set by potentiometer VR1, the GP4 output, pin 3, goes high and switches NPN transistor Q1 on. This powers the coil of the 30A relay (RLY1) to disconnect mains power from the pump.

Red LED3, also connected to pin 3 of IC1 via a 1kΩ resistor will also light up, to indicate a fault condition. A 1N4004 diode (D5) is used to quench the back-EMF from the relay's coil when Q1 is switched off.

The timer is reset by pressing Reset switch S2. This pulls the $\overline{\text{MCLR}}$ input, at pin 4 of IC1, low to restart the program within IC1. $\overline{\text{MCLR}}$ is pulled high via a 10kΩ resistor while the 10μF capacitor between ground and the $\overline{\text{MCLR}}$ input ensures that IC1 is given a sufficient reset period. The capacitor keeps the input low for sufficient time for a device reset, even if S2 is only momentarily pressed.

Pushbutton S1 and yellow LED2 provide an EXTEND function. This is to allow a pump or compressor to run for much longer than the usual operating period when it is first turned on – to allow the system to come up to operating pressure.

When the pump finally turns off, LED2 will go out and then the timer is ready for the next on cycle of the pump (or compressor).

Power

Power for the timer circuit is provided by a Vigortronix switchmode module (REG1), which converts the incoming 230VAC into 12V DC output, to drive the 12V relay coil. Its 12V output is also fed to a 5V 3-terminal regulator (REG2) to power the microprocessor and the LEDs.

The incoming 230VAC supply connects to REG1 and a metal-oxide Varistor (MOV1), the latter to suppress transients, in conjunction with a 100nF X2-rated capacitor, which provides a degree of hash filtering.

REG1's 12V DC output is filtered with a 4.7μH inductor and 47μF capacitor.

We have used the switchmode module because it is cheaper than a conventional small mains transformer, bridge rectifier and capacitor supply, and it is also very efficient. This approach results in a very low standby power of less than 0.15W.

Also, the 5V regulator draws a very low quiescent current, less than 15μA, and most of the time the microprocessor is in sleep mode if it is not providing a timing function.

Typically, IC1 wakes up every 2.3 seconds and checks for a DC voltage at its AN0 input, pin 7. If present, that indicates that the pump is running and the timing function should be started.

Note that the relay's contacts are wired so that 230VAC is connected via the current transformer to the mains output socket when the relay is not energised.

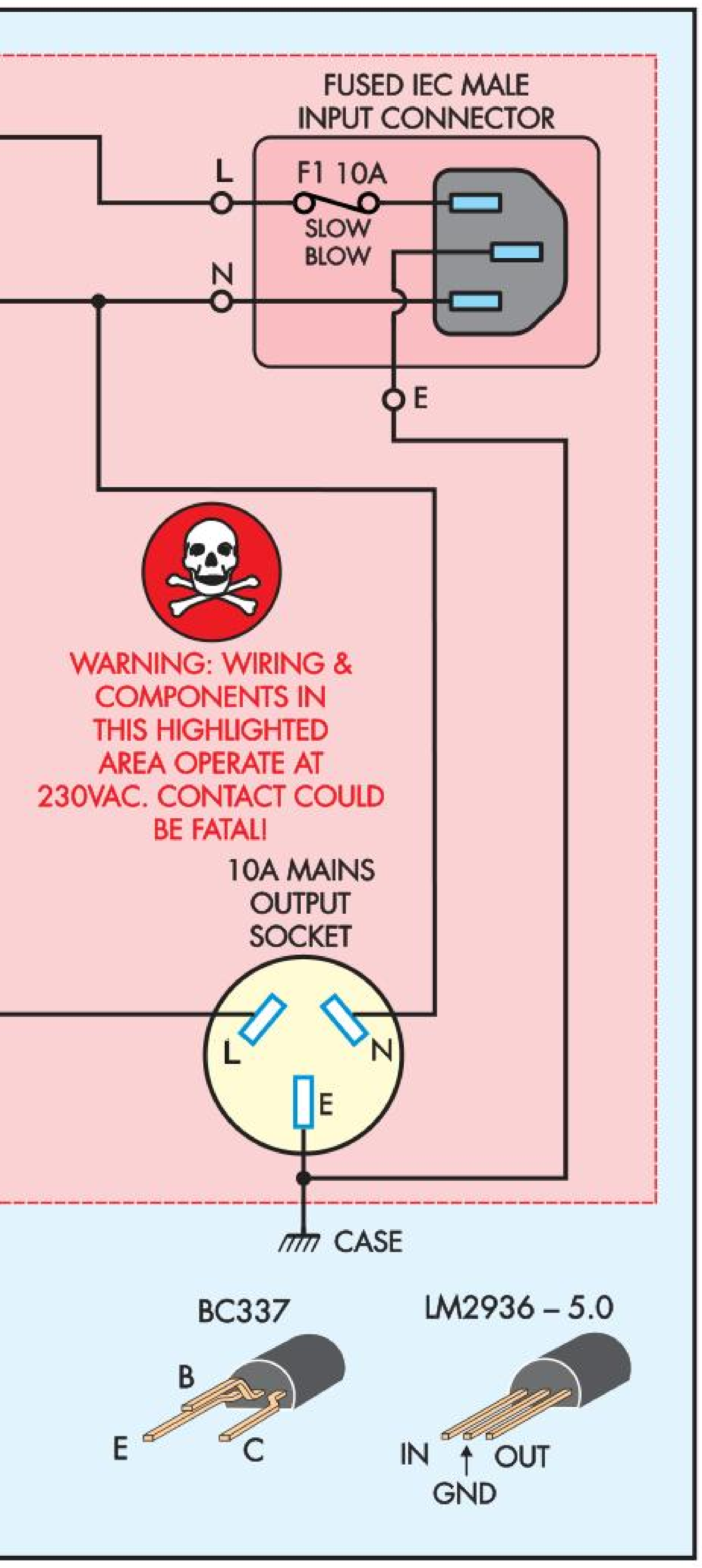
Specifically, we are using the NC (normally connected) and COMmon contacts. The relay is only energised if a fault condition is detected and that breaks the mains connection to the pump. Even then, the overall power consumption of the timer is only about 1.3W.

So that describes the circuit operation of the *Cyclic Pump Timer*. Now let's have a look at Fig.2, which is the circuit of the simpler 230VAC Timer.

It is similar to that of Fig.1 except that all the components associated with the current transformer (in the green shaded section of Fig.1) are omitted.

This version of the circuit only has two LEDs, green LED1 and red LED2. The other important difference is the contact wiring of the relay. In this case, the relay is turned **on** during the selected time (as set by potentiometer VR1) and so the 230VAC passes via the NO (normally off) and COMmon contacts. So this means that when the relay is energised, the appliance connected to the mains output socket is powered and that only happens when the timer is started, by pressing switch S1.

When timing is in progress, LED2 flashes and the GP4 output of IC1, pin 3, is high to turn on transistor Q1 and the


FUSED IEC MALE INPUT CONNECTOR
L
N
F1 10A
SLOW BLOW
E
WARNING: WIRING & COMPONENTS IN THIS HIGHLIGHTED AREA OPERATE AT 230VAC. CONTACT COULD BE FATAL!
10A MAINS OUTPUT SOCKET
L
N
E
CASE
BC337
B
E
C
LM2936 – 5.0
IN
OUT
GND

relay coil. At the end of the selected time period, Q1 is turned off to de-energise the relay and LED2 stops flashing. Of course, the timing period can also be terminated by pressing S2, the Stop button.

Note that both versions of the circuit, Fig.1 and Fig.2, use the same programmed microprocessor. It needs to detect which circuit it has been installed in and then it selects the correct software routine. How does it do this?

In both versions of the circuit, there is a 100kΩ resistor connected between pin 7 (AN0) and 0V but in the circuit of Fig.1, a 10µF capacitor is also present (as part of the current transformer circuitry).

Each time power is applied to the micro, it briefly pulls the AN0 pin high via an internal pullup resistor. After the pullup is switched off, 100 milliseconds later it measures the voltage at pin 7. If the voltage is above 200mV, that tells the micro that it is connected in the *Cyclic Pump Timer* circuit and it operates accordingly. On the other hand, if the voltage at pin 7 is very close to zero, that means that there is no 10µF capacitor present and the micro is in the circuit of Fig.2.

By taking this approach, we can use the same microprocessor for both versions of the *Timer* and there is no need for the constructor to make any program selection by means of, for example, links.

Other notes on the software

As already noted, IC1 is normally in sleep mode, during which it consumes minimal power. It wakes up each time its watchdog timer times out (every 2.3 seconds) or if switch S1 is closed. For the *Cyclic Pump Timer*, each time IC1 is woken by the watchdog timer, it checks the AN0 input for a DC voltage above 200mV, as noted above.

Switch S1 is the Extend button for the *Cyclic Pump Timer* and the Start button for the straight *230VAC Timer*. When S1 is pressed, this either wakes IC1 from sleep or if it is already awake, the GP2 input is changed to a low output that drives the indicator LED (LED2).

The software then checks if the GP2 pin is low, setting the extend feature for the *Cyclic Pump Timer* (or starting the *230VAC Timer*). The GP2 output reverts to an input unless the LED is required to be driven independently of the switch being pressed.

Switch S2 is the Reset for the *Cyclic Pump Timer* and the stop button for the *230VAC Timer*. This connects to the master clear ($\overline{\text{MCLR}}$) input of IC1. Pressing and releasing this switch causes the software to restart, clearing the timer.

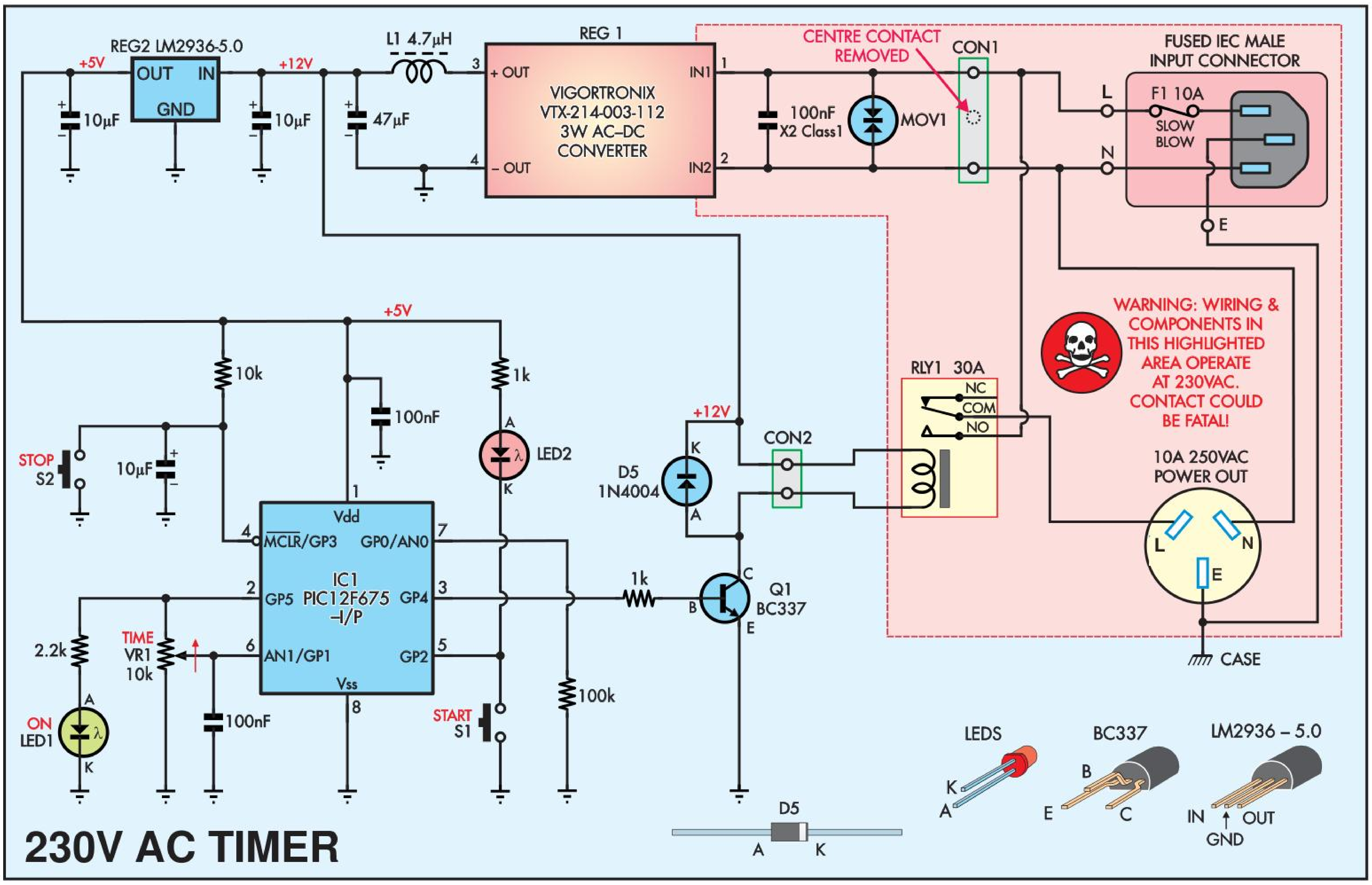
Cycling timer assembly

Both versions of the *Timer* use two PCBs, both of which are available from the *EPE PCB Service*. One PCB is coded 10108161 and measures 85 × 78mm. The second is coded 10108162 and measures 83 × 35.5mm. The two PCBs are housed in a diecast box measuring 119 × 94 × 57mm and connected together with a short IDC cable.

As already noted, the major difference between the two versions is that the current transformer and its associated components are only used in the *Cyclic Pump Timer*.

Fig.3 shows the two PCB overlays for the *Cyclic Pump Timer*. You can begin construction by installing the resis-

Fig.2: (below) the general-purpose timer is simpler – it doesn't have the current-sensing circuitry. Power to the appliance is cut when a preset time is reached.


REG2 LM2936-5.0
+5V
OUT
IN
GND
+12V
10µF
10µF
L1 4.7µH
47µF
REG 1
3
+ OUT
4
– OUT
VIGORTRONIX VTX-214-003-112 3W AC–DC CONVERTER
IN1
IN2
1
2
100nF X2 Class1
MOV1
CENTRE CONTACT REMOVED
CON1
FUSED IEC MALE INPUT CONNECTOR
L
N
F1 10A
SLOW BLOW
E
+5V
10k
100nF
1k
A
LED2
K
λ
+12V
K
D5 1N4004
A
CON2
RLY1 30A
NC
COM
NO
WARNING: WIRING & COMPONENTS IN THIS HIGHLIGHTED AREA OPERATE AT 230VAC. CONTACT COULD BE FATAL!
10A 250VAC POWER OUT
L
N
E
CASE
STOP S2
10µF
1
Vdd
4
MCLR/GP3
GP0/AN0
7
2
GP5
IC1 PIC12F675 –I/P
GP4
3
6
AN1/GP1
GP2
5
Vss
8
1k
B
C
E
Q1 BC337
100k
2.2k
TIME VR1 10k
100nF
ON LED1
A
K
START S1
D5
A
K
LEDS
K
A
BC337
B
E
C
LM2936 – 5.0
IN
OUT
GND
230V AC TIMER

tors on each PCB, using a multimeter to check the value of each one before inserting it on the PCB.

Then install inductor L1, diodes D1 to D5 and ZD1 (if used). Note that D5 is a 1N4004, while D1-D4 are 1N4148s. The inductor looks like a fat resistor and has four colour bands: yellow (4), violet (7), gold (decimal point 0.1) and silver, signifying a 4.7µH inductor with a tolerance of ±10%.

REG2 on the smaller PCB and Q1 on the main PCB can be soldered in next. Don't get the regulators mixed up as they look similar, apart from their type markings. REG2 needs to be installed so the top of the package is no higher than 8.5mm above the PCB. A socket can be used with IC1 on the smaller PCB if you wish. Take care to orient each with the correct polarity.

We used PC stakes for the GND terminal on the main PCB, plus the connections to switches S1, S2 and potentiometer VR1 on the smaller board. Five PC stakes are used for VR1; three for the potentiometer terminal connections, one for the GND and the remaining two for connection of the potentiometer body to the PCB.

Cut the shaft of VR1 so that it is 10mm long (measured from the point where the shaft enters the threaded bush) and then solder it to the five PCB stakes.

To ensure a good connection to the potentiometer body, scrape any coating off the metal adjacent to where it will solder to the PC stake, then 'tin' it with solder before actually soldering it in place.

LED1 to LED3 are mounted so the tops of their lenses are 13mm above the top surface of the PCB. Make sure the longer lead of each LED (the anode) is inserted in the 'A' position on the PCB. LED1 is green, LED2 is yellow and LED3 is red.

You can check LED colour using the diode test on a multimeter. The LED should faintly glow when the probes are connected to the correct pins.

The four 10µF electrolytic capacitors are mounted so that they sit side-on and project out from the side of the PCB (see photo). This is so they don't foul the lid of the case when the PCB is mounted. Then install the two 100nF capacitors on the same PCB.

The 47µF electrolytic capacitor is installed on the main PCB next, again taking care with its polarity. Then fit the 100nF X2 class capacitor and MOV1. These are not polarised.

Next, install REG1, current transformer T1 and the terminal blocks, CON1 and CON2. Note that CON1 is a 3-way terminal block with the centre terminal removed (remove the screw and prise out the terminal with a fine screwdriver).

The relay is mounted with the coil terminals toward CON2, using M3 × 10mm screws and M3 nuts. Wire the relay coil terminals to CON2 using 250VAC-rated wire. The terminals and soldered connections are then covered in heatshrink tubing with the two wires tied together with a cable tie.

The two PCBs are connected using a 90mm length of 10-way IDC cable, with an IDC connector at each end. Use the captive header for CON4 and the box header and plug for CON3. Feed the ribbon cable through the connector and clamp it down. The clamping can be done with a G clamp and suitable pieces of wood placed on top and bottom to protect the connector. See the overlay diagram as a guide to the correct wire orientation.

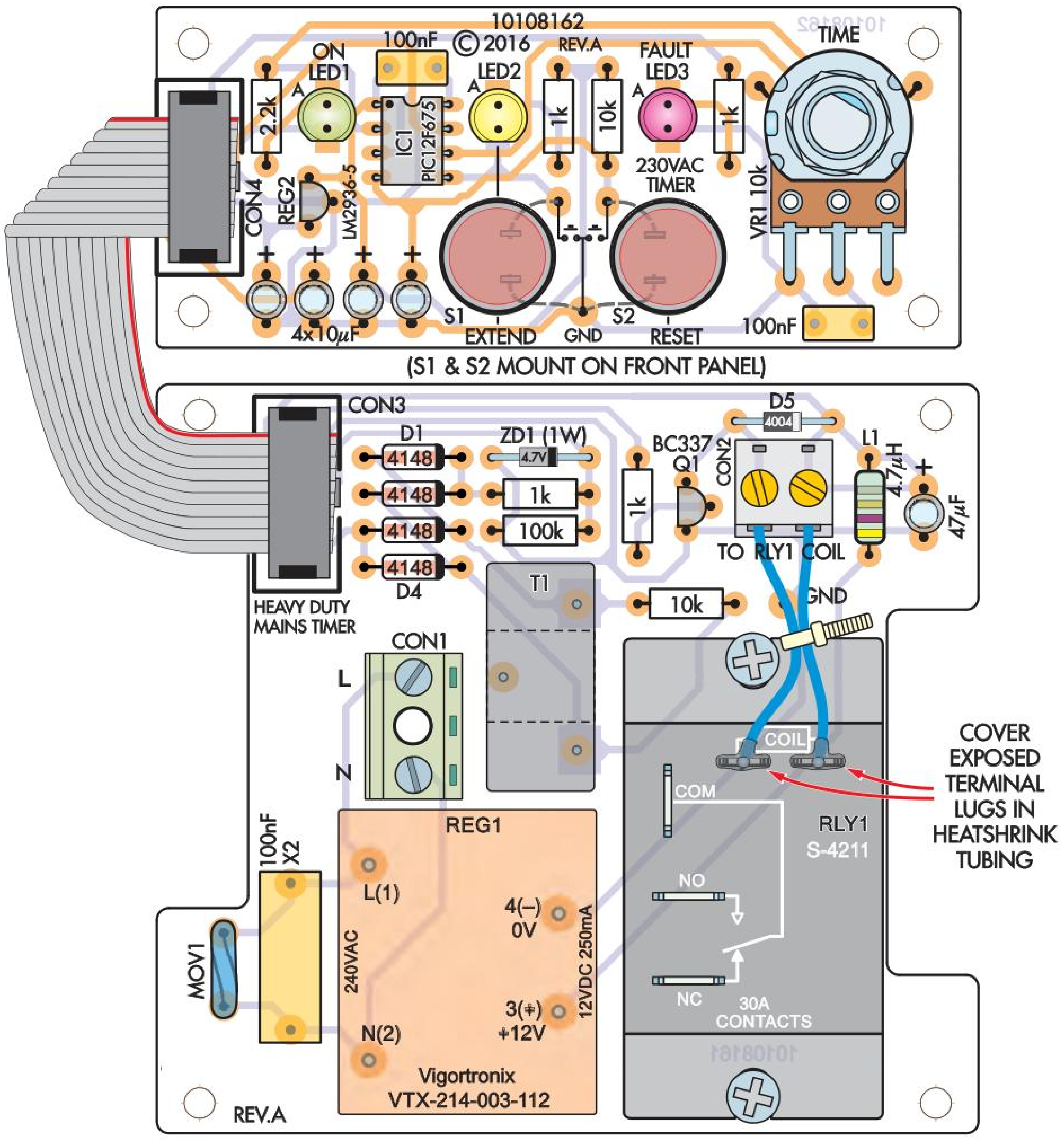
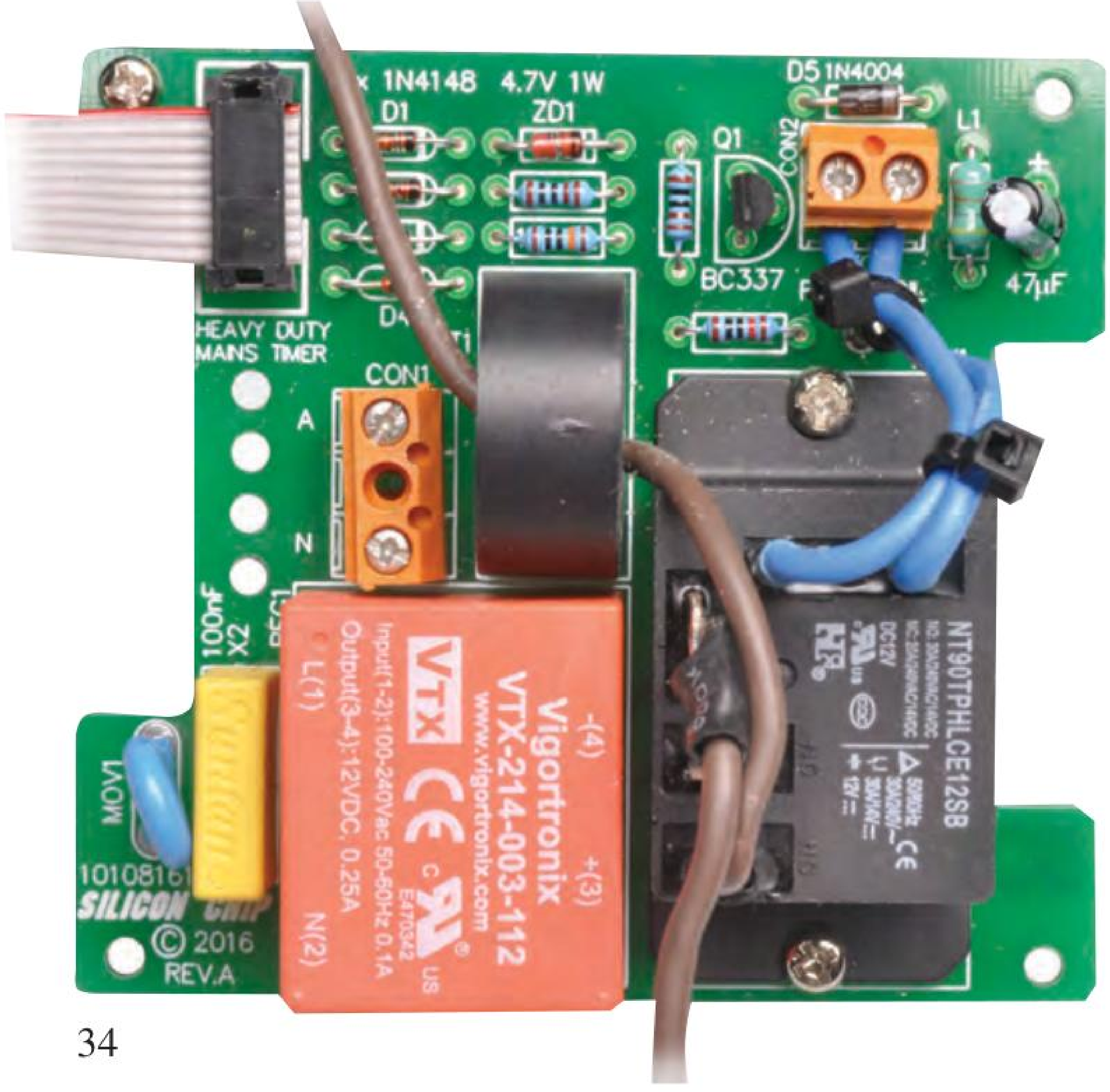
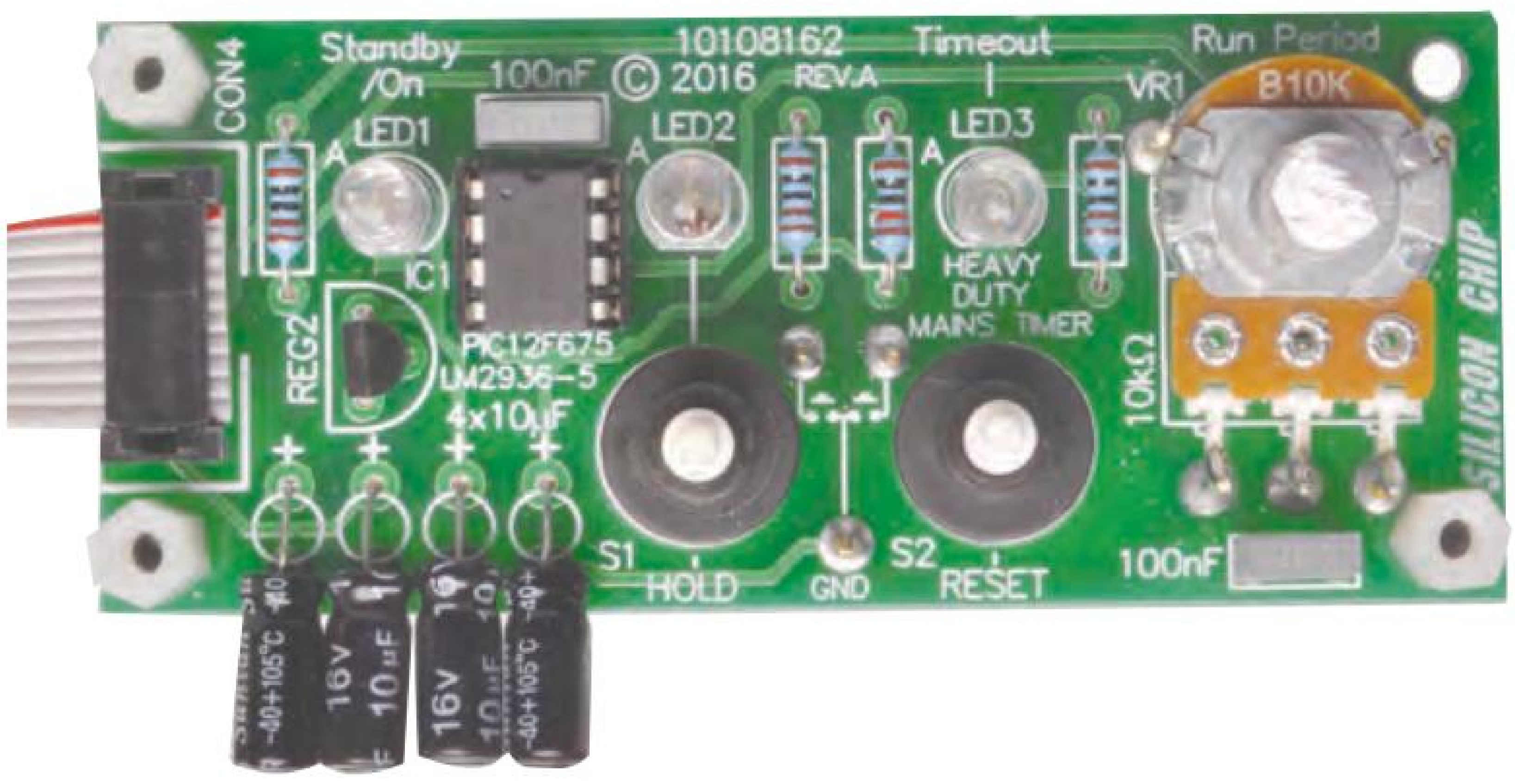
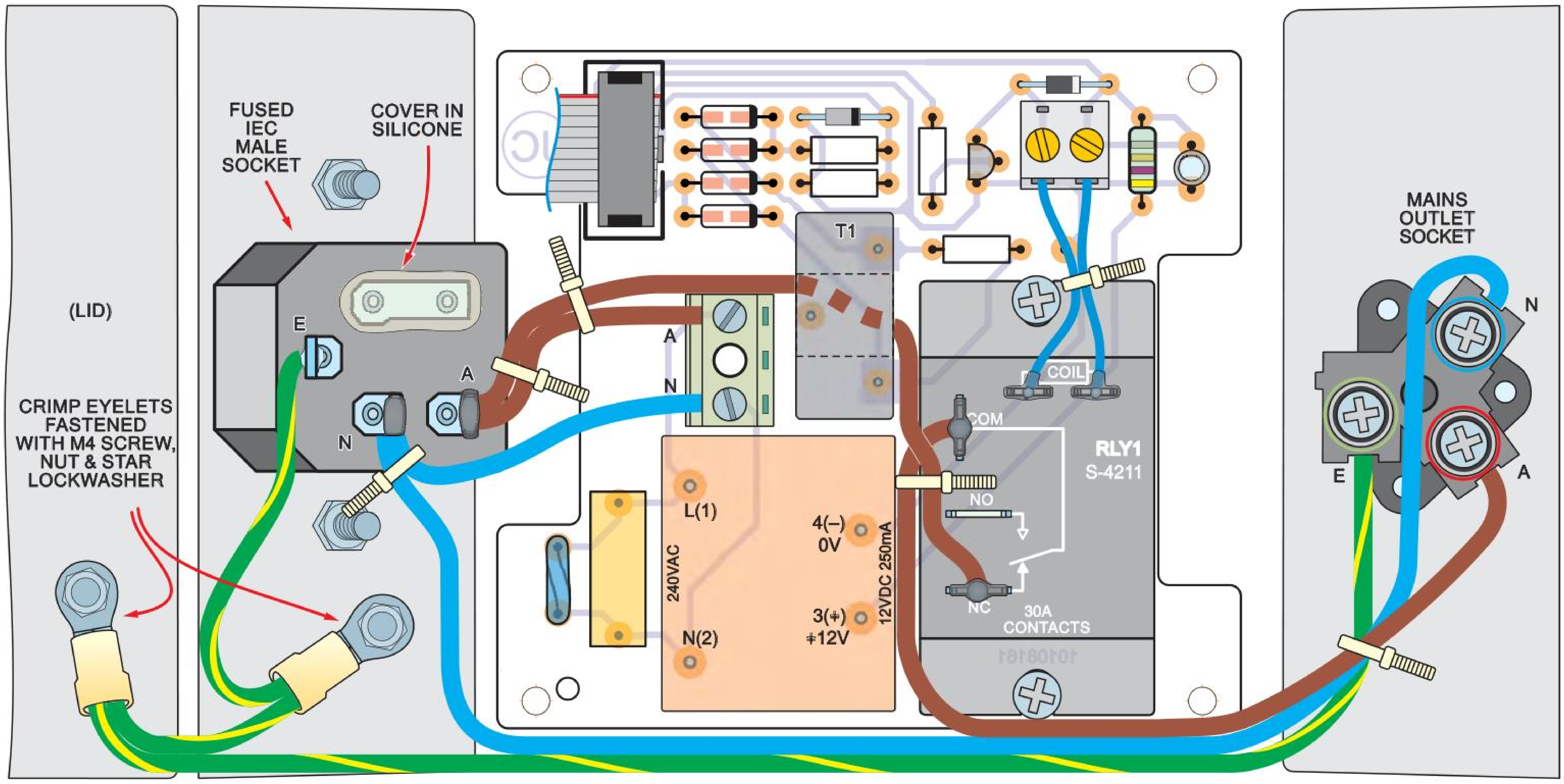

10108162
© 2016
REV.A
TIME
ON
LED1
100nF
LED2
FAULT
LED3
A
2.2k
IC1
PIC12F675
1k
10k
1k
230VAC
TIMER
VR1 10k
CON4
REG2
LM2936-5
4x10µF
S1
EXTEND
GND
S2
RESET
100nF
(S1 & S2 MOUNT ON FRONT PANEL)
CON3
D1
4148
ZD1 (1W)
4.7V
1k
100k
D4
D5
4004
BC337
Q1
CON2
L1
4.7µH
47µF
1k
TO RLY1 COIL
GND
T1
10k
HEAVY DUTY
MAINS TIMER
CON1
L
N
COIL
COM
COVER
EXPOSED
TERMINAL
LUGS IN
HEATSHRINK
TUBING
REG1
RLY1
S-4211
100nF
X2
L(1)
4(–)
0V
240VAC
12VDC 250mA
NO
MOV1
3(+)
+12V
N(2)
NC
30A
CONTACTS
Vigortronix
VTX-214-003-112
10108161
REV.A

Fig.3 (above) shows the PCB layout for version 1, the *Cyclic Timer*. Match this with the photos below which are close to same size.


1N4148
4.7V 1W
D1
ZD1
D5 1N4004
Q1
CON2
L1
BC337
47µF
HEAVY DUTY
MAINS TIMER
CON1
A
N
100nF
X2
MOV1
Vigortronix
VTX-214-003-112
10108161
SILICON CHIP
© 2016
REV.A


CON4
Standby
/On
100nF
10108162
© 2016
REV.A
Timeout
Run Period
VR1
B10K
LED1
LED2
LED3
IC1
REG2
HEAVY
DUTY
MAINS TIMER
PIC12F675
LM2936-5
4x10µF
10kΩ
SILICON CHIP
S1
HOLD
GND
S2
RESET
100nF
16V
10µF



NOTE: COVER EXPOSED TERMINAL LUGS WITH HEATSHRINK TUBING

Fig.4: here's the wiring diagram for the *Cyclic Timer* (version 1). Remember that you are dealing with mains voltages so ensure that all cabling is fully secured with cable ties, as shown here.

The next step is to drill the holes and make the cutouts in the diecast case and its lid. You will need to download the drilling template for this task from the *EPE* website (UK constructors must ignore the 'Mains GPO Cut out' and cut a hole to fit a UK socket – see p.30).

Make all the cutouts in the base of the case first and then then temporarily install the IEC connector and mains outlet socket. Then sit the main PCB in the box, positioned so it just clears the outlet. Mark out the four holes to mount the PCB on the base of the case and drill these at 3mm in diameter. Counter-bore the holes if using countersunk screws.

The main PCB is mounted on tapped 9mm nylon spacers with M3 × 6mm screws to attach the spacers to the PCB and to the box.

Having drilled the lid of the case, three 9mm spacers are attached to the top side of the smaller PCB. Note that no spacer is used in the corner next to the potentiometer.

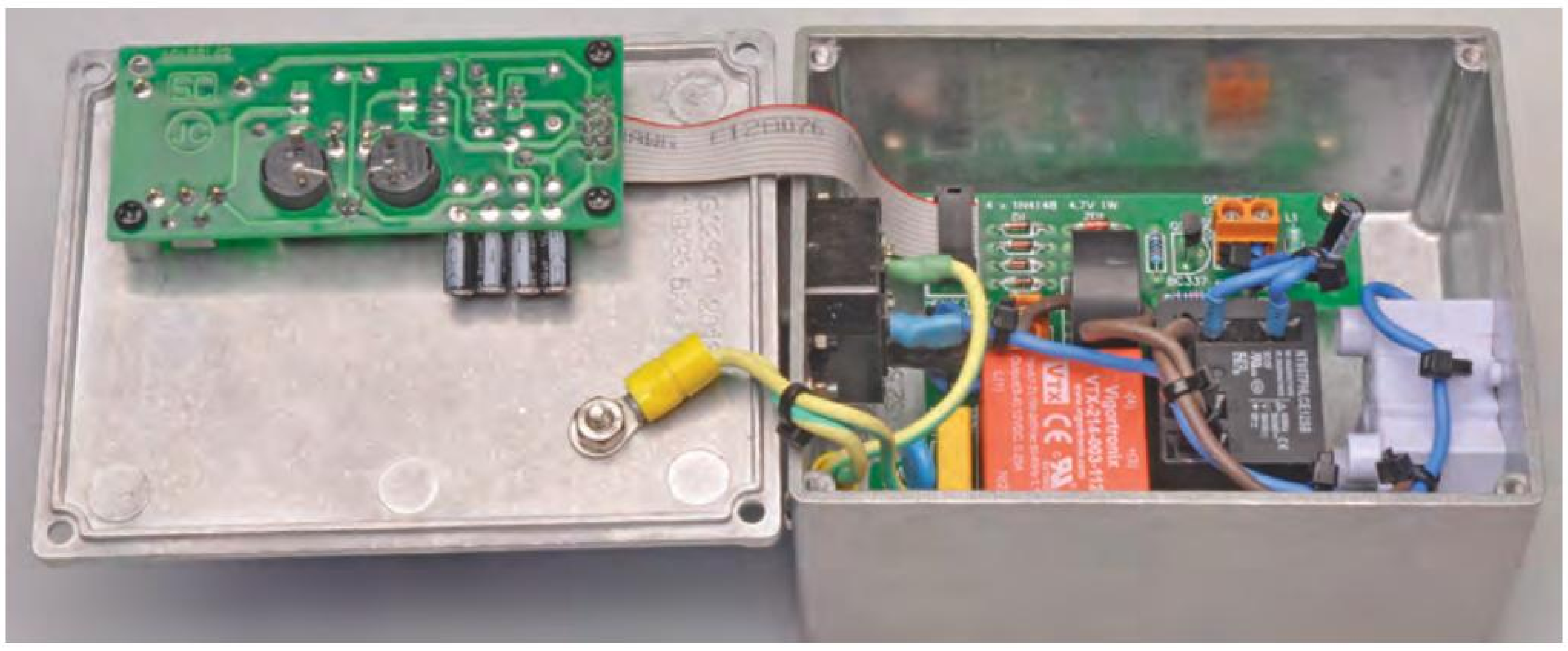
Instead, the PCB is retained by the nut on the potentiometer. Fit the potentiometer and switches with lockwashers and install all three, making sure they have the correct orientation for the switch terminals. Then fit the board to the lid and use tinned copper wire to connect the switch terminals to the three pads on the PCB.

Panel label

By the way, the front panel artwork is also available from the *EPE* website. Print off the label to suit the timer you are building.

To produce a front panel label, you have several options. One is to print onto clear overhead projector film (using film suitable for your type of printer and as a mirror image so the printed side is protected against the lid). Attach to the lid with clear silicone sealant.

Alternatively, you can print onto an A4 sized synthetic 'Dataflex' sticky label that is suitable for inkjet printers or a 'Datapol' sticky label for laser printers. Then affix the label using the sticky adhesive back. Cut out the required holes with a hobby knife.



Here's how it all fits in the diecast case. Note the 2nd PCB fitted to the lid of the case via an IDC cable, with the electrolytic capacitors mounted parallel with the PCB so they can fit. Also note the earth lug firmly secured to the case lid.

Completing the wiring

Follow the diagram of Fig.4 to complete the wiring. Use 250VAC 10A insulated hookup wire for the live (brown), neutral (blue) and earth (green/yellow stripe) connections.

These wires can be obtained by stripping off the outer sheath of a short length of surplus 3-core 250VAC cord.

The wires are soldered to the terminals of the IEC connector, with the bare terminals covered in heatshrink tubing. When soldering, make sure the wires are first passed through the terminal hole and the wires bent back onto the terminal. Ensure the terminal and wire are heated sufficiently and that the solder flows onto the terminal and wire for a good joint.

The IEC connector is secured to the case using M3 screws, star washers and M3 nuts.

There are two wires used for the live and neutral connections with one set of live and neutral wires going to CON1. The second neutral wire connects to the mains socket and the live wire to a relay contact.

For version 1, this live wire must also pass through the current transformer.

Earth wiring is done using a continuous length of wire between the IEC connector earth terminal and the mains outlet earth. Insulation is pared back where this is to be terminated to the crimp eyelets. Use a crimping tool to clamp the wires into the eyelet crimp

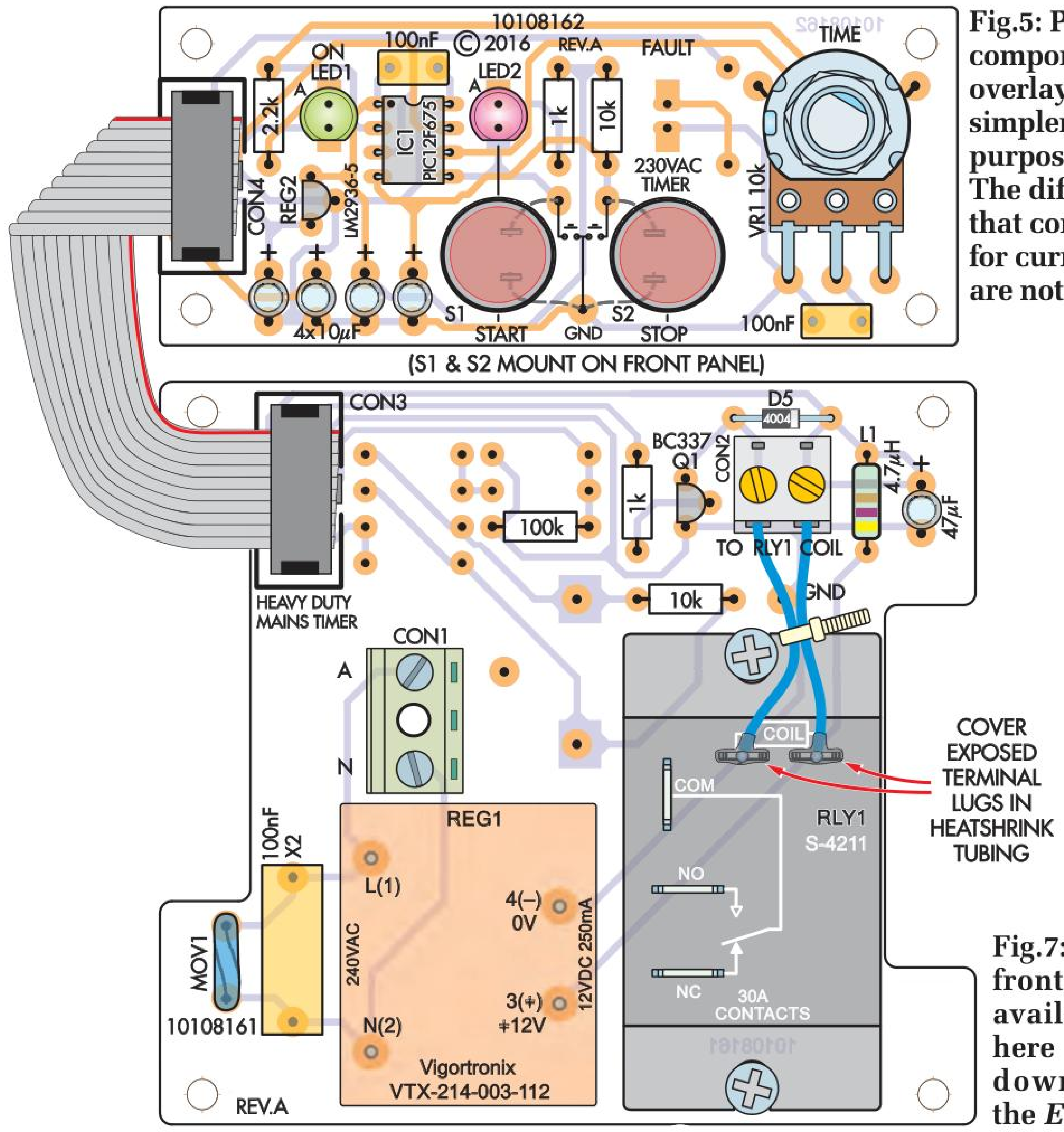

10108162
© 2016
REV.A
ON
LED1
100nF
FAULT
TIME
2.2k
LED2
IC1 PIC12F675
1k
10k
CON4
REG2
LM2936-5
230VAC TIMER
VR1 10k
4x10µF
S1
START
GND
S2
STOP
100nF
(S1 & S2 MOUNT ON FRONT PANEL)
CON3
D5
4004
BC337 Q1
CON2
L1
4.7µH
47µF
100k
1k
TO RLY1 COIL
10k
GND
HEAVY DUTY MAINS TIMER
CON1
A
N
COIL
COM
COVER EXPOSED TERMINAL LUGS IN HEATSHRINK TUBING
RLY1
S-4211
NO
NC
30A CONTACTS
REG1
L(1)
4(–) 0V
3(+) +12V
N(2)
240VAC
12VDC 250mA
100nF X2
MOV1
10108161
REV.A
Vigortronix VTX-214-003-112

Fig.5: PCB component overlay for the simpler, general-purpose timer. The difference is that components for current sensing are not required.

connection. You can solder the wire also to the eyelet to ensure it is firmly attached. Secure each eyelet to the case and lid using an M4 screw, star washer and M4 nut.

When finished, check your work carefully. Don't forget to install the fuse in the IEC connector. Screw on the lid and apply power.

No setting up is required as the microprocessor senses whether the current transformer components are installed (or not) and then uses the required program.

As noted in the specifications, the threshold current to start the timer function is 700mA AC. If you want to increase the sensitivity, loop the live wire through the current transformer twice for a 350mA AC threshold, or three times for 233mA AC.

Note that all soldered terminals should be covered in heatshrink tubing. All other details can be noted from the internal photos.

Building the 230VAC Timer

If you're not building the *Cyclic Pump Timer*, use the PCB overlay diagram of Fig.5 and the wiring diagram of Fig.6 instead.

As already described, this simpler version of the *Timer* omits all the components associated with current transformer T1, with the exception of the 100kΩ resistor connected to pin 7 of IC1, plus LED3 and its 1kΩ resistor.

Note also the slightly different wiring of the contacts of the relay and its 1kΩ resistor. Last, LED2 is red (not yellow).

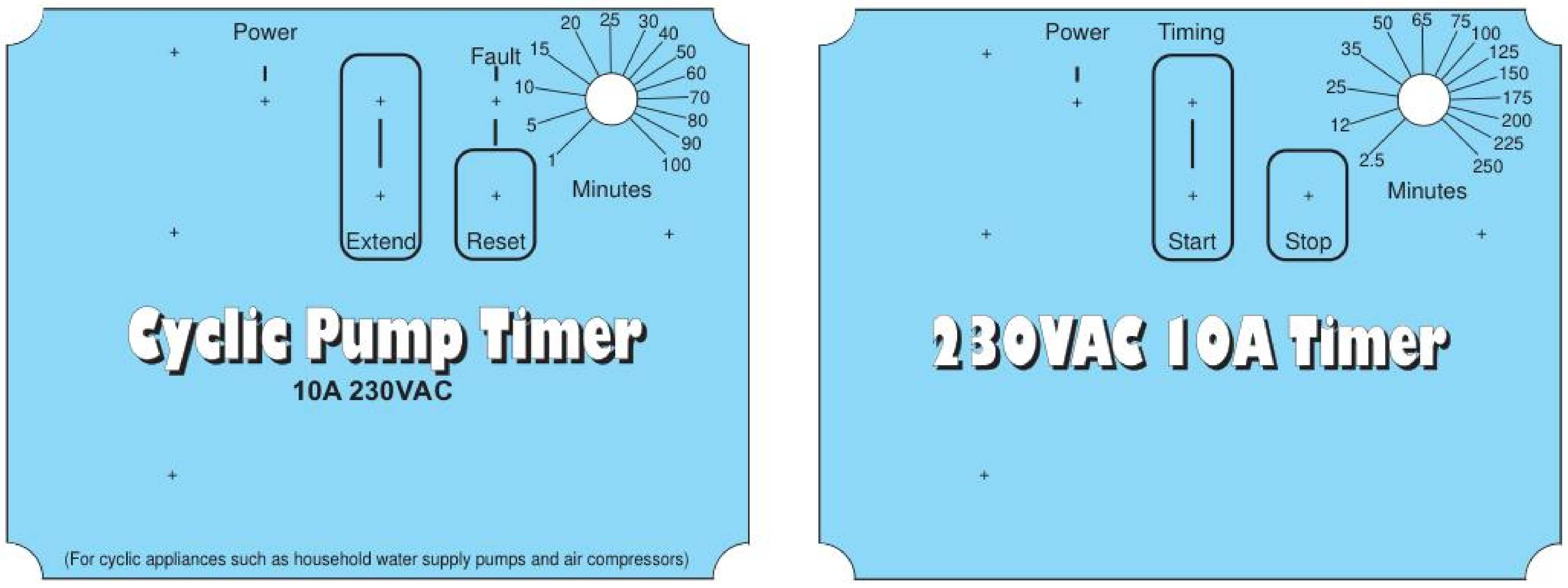
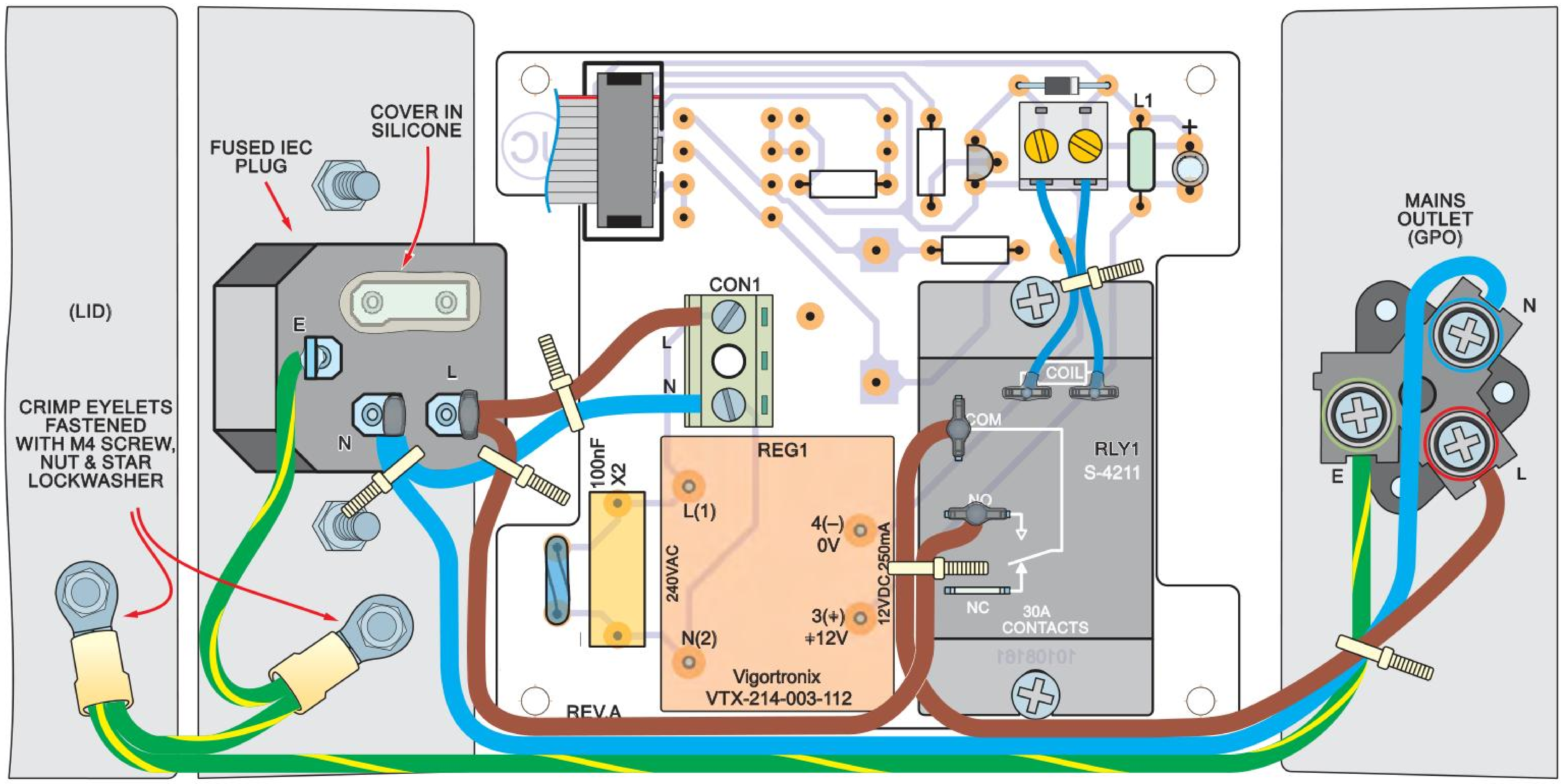

Power
Fault
Extend
Reset
Minutes
1
5
10
15
20
25
30
40
50
60
70
80
90
100
Cyclic Pump Timer
10A 230VAC
(For cyclic appliances such as household water supply pumps and air compressors)
Power
Timing
Start
Stop
Minutes
2.5
12
25
35
50
65
75
100
125
150
175
200
225
250
230VAC 10A Timer

Fig.7: two different front panels are available, shown here half size. – download from the *EPE* website.


(LID)
FUSED IEC PLUG
COVER IN SILICONE
E
L
N
CRIMP EYELETS FASTENED WITH M4 SCREW, NUT & STAR LOCKWASHER
CON1
L
N
100nF X2
REG1
L(1)
4(–) 0V
3(+) +12V
N(2)
240VAC
12VDC 250mA
Vigortronix VTX-214-003-112
REV.A
L1
COIL
COM
RLY1
S-4211
NO
NC
30A CONTACTS
10108161
MAINS OUTLET (GPO)
N
E
L

NOTE: COVER EXPOSED TERMINAL LUGS WITH HEATSHRINK TUBING

Fig.6: there are slight differences in this, the general-purpose timer and the *Cyclic Timer* shown earlier. Make sure you follow this diagram when building the general purpose timer.

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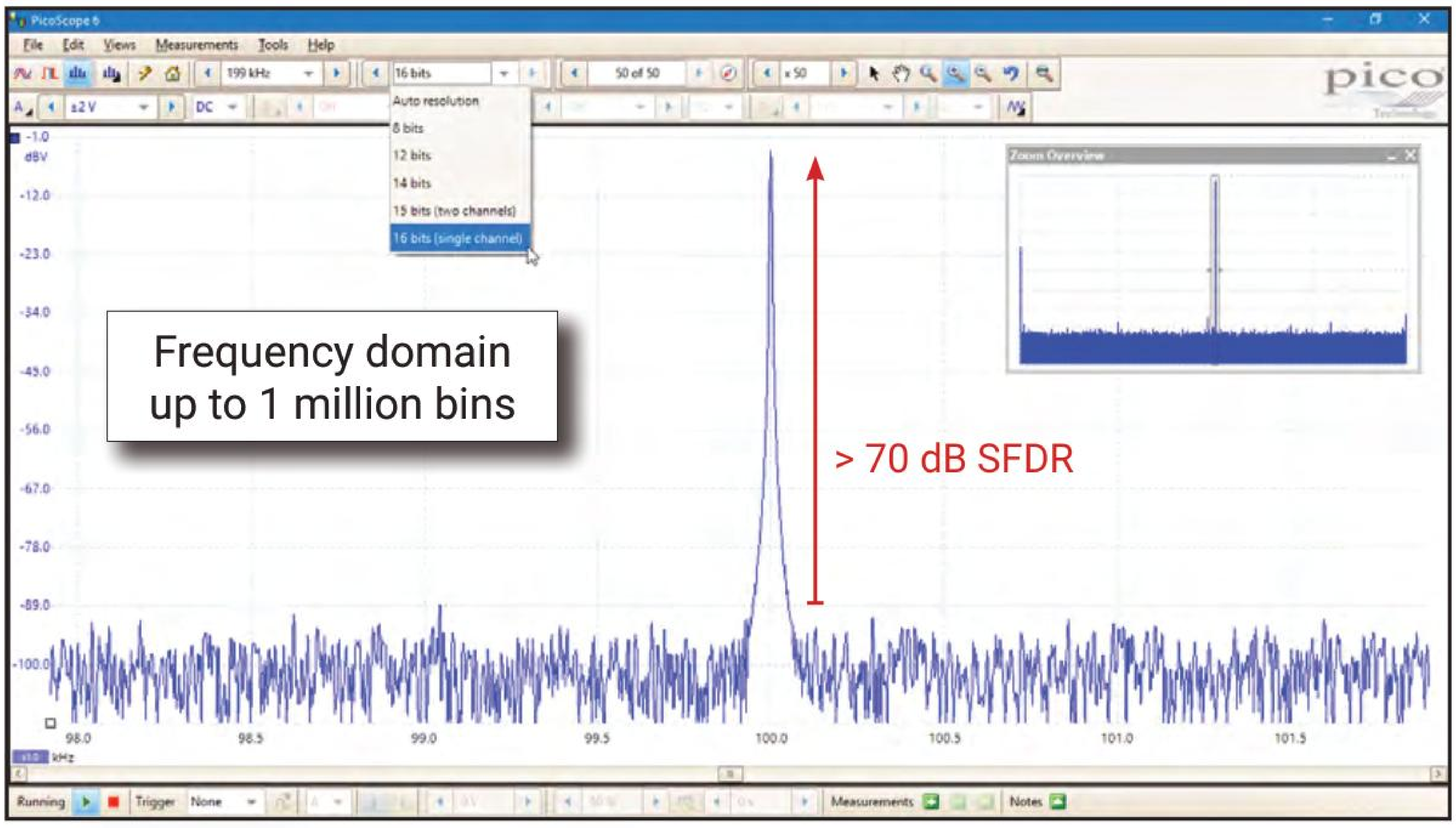
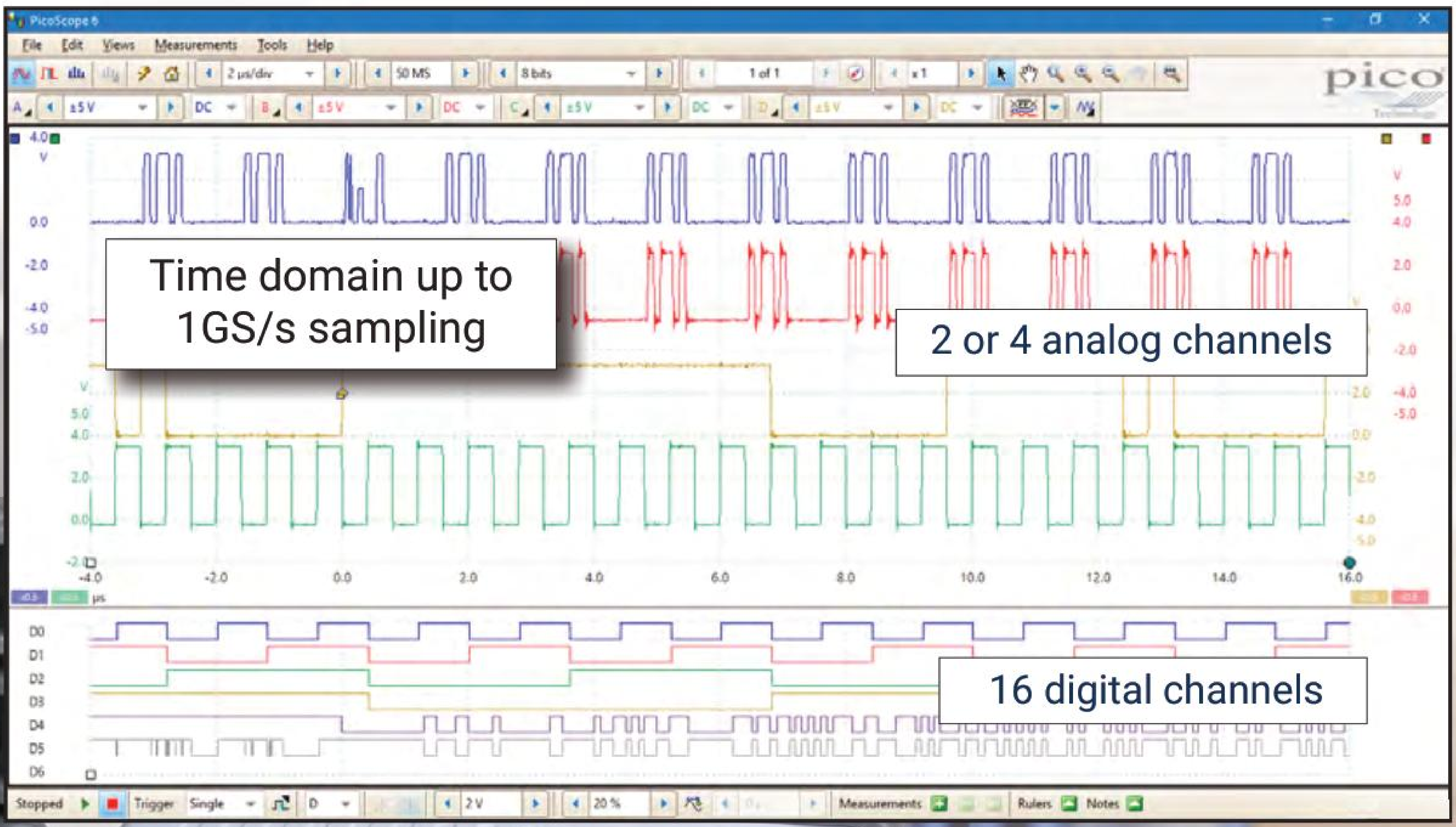
- 16 digital channels (on MSO models)
- Serial decoding as standard (18 protocols)
- 70 dB SFDR at 100 kHz


PicoScope 6
File Edit Views Measurements Tools Help
199 kHz
16 bits
Auto resolution
8 bits
12 bits
14 bits
15 bits (two channels)
16 bits (single channel)
50 of 50
±2 V
DC
Zoom Overview
dBV
-1.0
-12.0
-23.0
-34.0
-45.0
-56.0
-67.0
-78.0
-89.0
-100.0
98.0
98.5
99.0
99.5
100.0
100.5
101.0
101.5
kHz
Running
Trigger None
Measurements
Notes

Frequency domain up to 1 million bins

> 70 dB SFDR


PicoScope 6
File Edit Views Measurements Tools Help
2 µs/div
50 MS
8 bits
1 of 1
±5 V
DC
-4.0
-2.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
µs
D0
D1
D2
D3
D4
D5
D6
Stopped
Trigger Single
2 V
20 %
Measurements
Rulers
Notes

Time domain up to 1GS/s sampling

2 or 4 analog channels

16 digital channels

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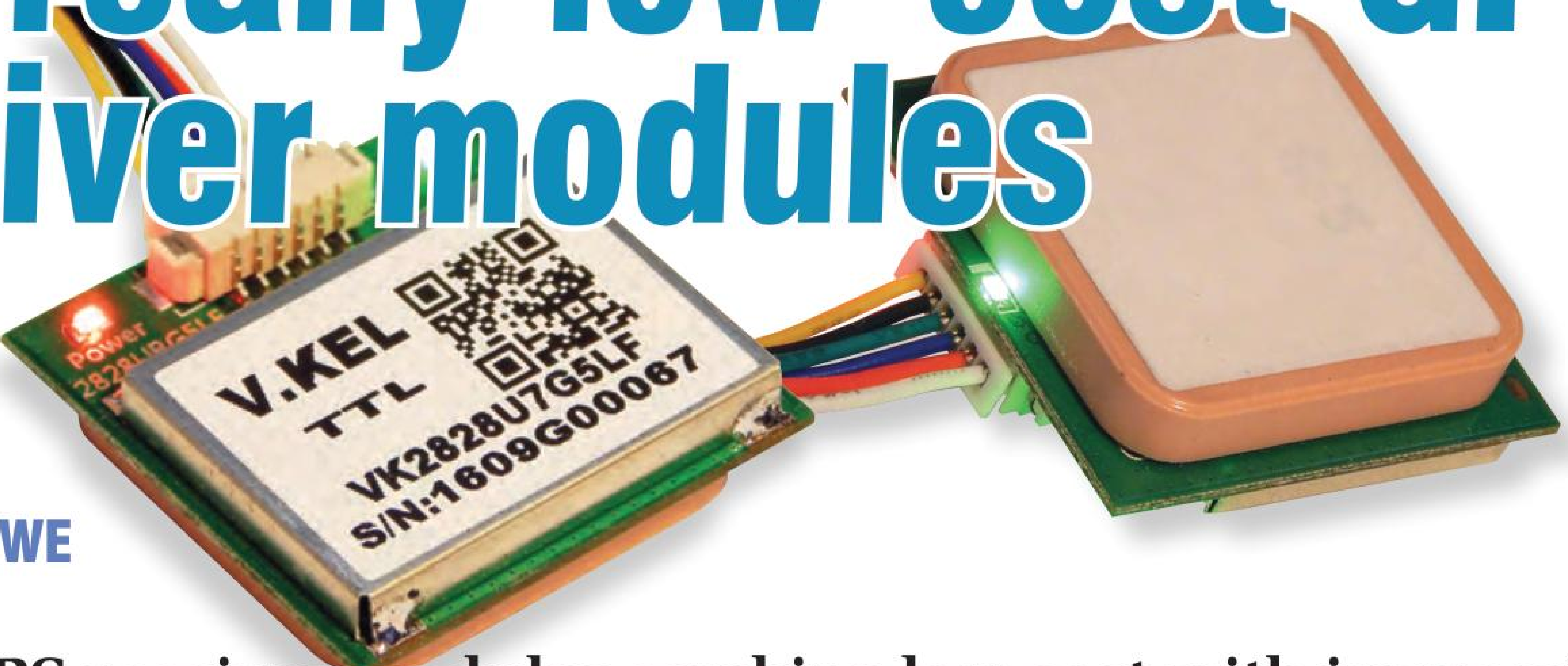
Two really low-cost GPS receiver modules



By JIM ROWE

These two GPS receiver modules combine low cost with impressive performance – making them very attractive for use in all kinds of projects. One is the V.KEL 'GMouse' VK2828U7G5LF, and the other is the u-blox Neo-7M.

Using Cheap Asian Electronic Modules Part 10: by Jim Rowe

Over the 10 years or so that GPS receiver modules have been available for use in electronic projects, they have not only improved significantly in performance but have also dropped dramatically in price.

For example, the Garmin GPS15L module we used in our GPS-derived Frequency Reference (Silicon Chip March-May 2009) cost £80 and also needed a separately powered outside antenna/LNA, which cost about half as much again.

At the time, we thought this was surprisingly cheap, but by 2013 the prices for similar modules had dropped to less than £35 – despite the fact that they were more sensitive and had a built-in ceramic 'patch' antenna.

Despite that price drop, technology and market forces keep marching on, and now you can buy a very compact GPS receiver module complete with ceramic patch antenna (the V.KEL Electronics VK2828U7G5LF) for under £10 on eBay. Alternatively, you can buy a similar unit (the u-blox Neo-7M) with separate patch antenna for a similar price from banggood.com, or AliExpress.

The two modules look a little different, as you can see from the photos. For the V.KEL 'GMouse', the ceramic patch antenna is mounted on the underside of the module's main PCB, while for the Neo-7M it is separate and connected to the receiver using a short length of thin coaxial cable. Both modules are built in China and they're both based on the same GPS receiver engine chip (the UBX-G7020-KT), made by Swiss firm u-blox Holding AG.

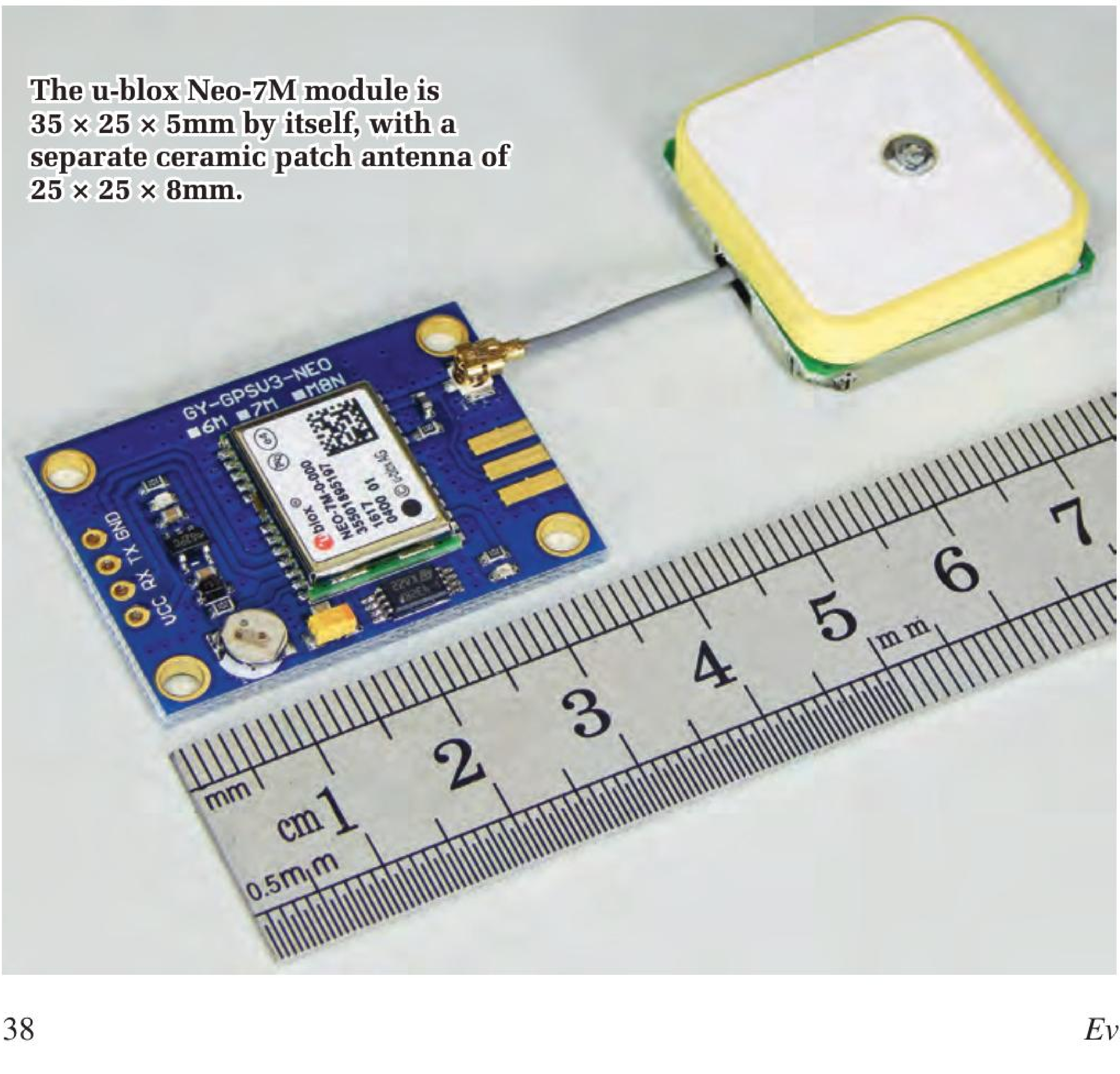
Founded in 1997 as a spin-off from the Swiss Federal Institute of Technology in Zurich, u-blox had delivered one million GPS receivers by 2004 and its 10 millionth receiver by 2008. In 2011, it acquired the Californian firm Fusion Wireless and in 2012 it acquired Finland-based Fastrax.

The firm now has offices in Finland, China and Japan, as well as in the US and many European countries. You can find more about them on their website at **www.u-blox.com**, including a data sheet on the UBX-G7020-KT engine chip and a full data sheet on the closely related Neo-7M module.

You can also get a comprehensive data sheet for the VK2828U7G5LF module from either of these websites:

- **www.vkelcom.com**
- **http://bit.ly/2zsA4s2**

As you can see from the block diagram in Fig.1, the UBX-G7020-KT GPS engine chip is impressive. It's a complete


The u-blox Neo-7M module is 35 × 25 × 5mm by itself, with a separate ceramic patch antenna of 25 × 25 × 8mm.

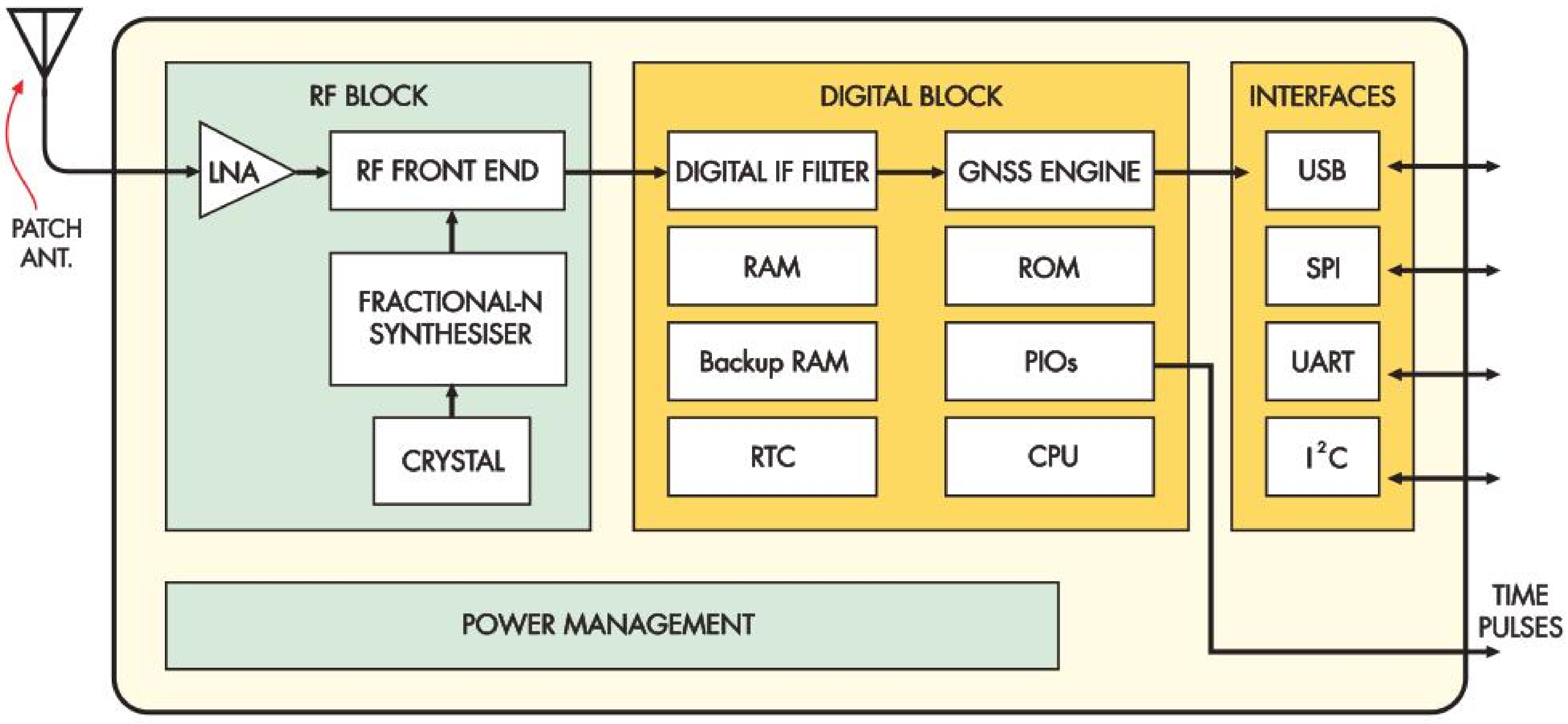

PATCH ANT.
RF BLOCK
LNA
RF FRONT END
FRACTIONAL-N SYNTHESISER
CRYSTAL
DIGITAL BLOCK
DIGITAL IF FILTER
GNSS ENGINE
RAM
ROM
Backup RAM
PIOs
RTC
CPU
INTERFACES
USB
SPI
UART
I²C
POWER MANAGEMENT
TIME PULSES

Fig.1: block diagram of the UBX-G7020-KT GPS engine chip. The whole chip is contained within a 5 × 5 × 0.6mm SMD package. Due to a multi-mode GNSS decoding engine, this chip can handle 56 channels of GPS, GLONASS or GALILEO. Note that the European GALILEO system is not yet operational.

GPS receiving system integrated inside a 5 × 5 × 0.6mm SMD package.

There's an RF/microwave front-end receiving block with an LNA (low-noise amplifier) and a crystal-derived fractional-N frequency synthesiser for the local oscillator, with its IF output fed to a digital block with a CPU controlling a digital IF filter and a multi-mode GNSS decoding engine that can handle 56 channels of either GPS or GLONASS (Russian version of GPS) satellite signals.

Supporting the rest of the digital block are ROM, RAM and backup RAM, RTC (real-time clock) and a number of programmable I/O sections – including one which provides configurable time pulse signals (0.25Hz-10MHz) with an RMS accuracy of 30ns. Finally, there's a selection of four different output interfaces: USB, SPI, UART and I^{2}C.

Additionally, the cold-start sensitivity of the UBX-G7020-KT chip is claimed as –148dBm, falling to –160dBm for reacquisitions. The time to first fix for a cold start is listed as 30 seconds, dropping to one second for a hot start. In short, it's an impressive little performer.

Inside the Neo-7M

So that's a glimpse of what's inside the UBX-G7020-KT chip itself. Now let's take a look at one of the modules using it, the Neo-7M. This measures 35 × 25 × 5mm for the module itself, with the separate patch antenna measuring 25 × 25 × 8mm. You'll find the Neo-7M's full circuit in Fig.2. (We don't have the full circuit details of the VK2828U7G5LF module, but it's likely to be quite similar.)

As you can see, there's not a lot in it apart from the UBX-G7020-KT receiver (IC1) and its matching active antenna, which is a ceramic patch antenna with onboard LNA. The antenna connects to the RF input of IC1 (pin 11) via a 20mm length of very small diameter coax and a pair of ultra-miniature U.FL coax connectors. DC power to operate the LNA is provided via inductor L1 and its series 22Ω resistor, connected to pin 9 of IC1.

The UBX-G7020 is designed to operate from a 3.3V supply. However, the module includes a low-dropout regulator (REG1) so that it can be connected directly to a 5V DC supply. Note that there's also a pill-sized rechargeable backup battery connected to pin 22 of IC1 which is charged via diode D1 and the series 1kΩ resistor when power is applied to the module.

But what's the purpose of IC2, a 32Kb (4KB) EEPROM? It is provided in order to save the UBX-G7020's configuration data, since many aspects of its configuration can be changed – such as the I/O port to be used, the frequency of its time-pulse output and so on.

The Neo-7M module leaves the factory with a default configuration where the UART and I^{2}C I/O ports are activated, with the UART I/O set for a bit rate of 9600 baud and '8N1' no-handshaking. The time-pulse frequency is also set for 1Hz. However, it's also programmed to save its configuration data in external memory, via the I^{2}C port, so that it can retrieve this information each time it's powered up.

The module designers have provided IC2 to save this configuration data, so if you want to change the Neo-7M's configuration, it's possible to do this by reprogramming IC2. In fact, most users probably won't want to do this, because the default configuration is likely to be suitable for the majority of common applications.

That's about it, apart from the two LEDs. Red LED1 is provided as a power indication, lighting up whenever +5V power is provided to the module via pin 4 of CON1. And green LED2 is connected via a second 1kΩ resistor to pin 3 of IC1, which is the time pulse output.

LED2 flashes once per second (with the default configuration), when the

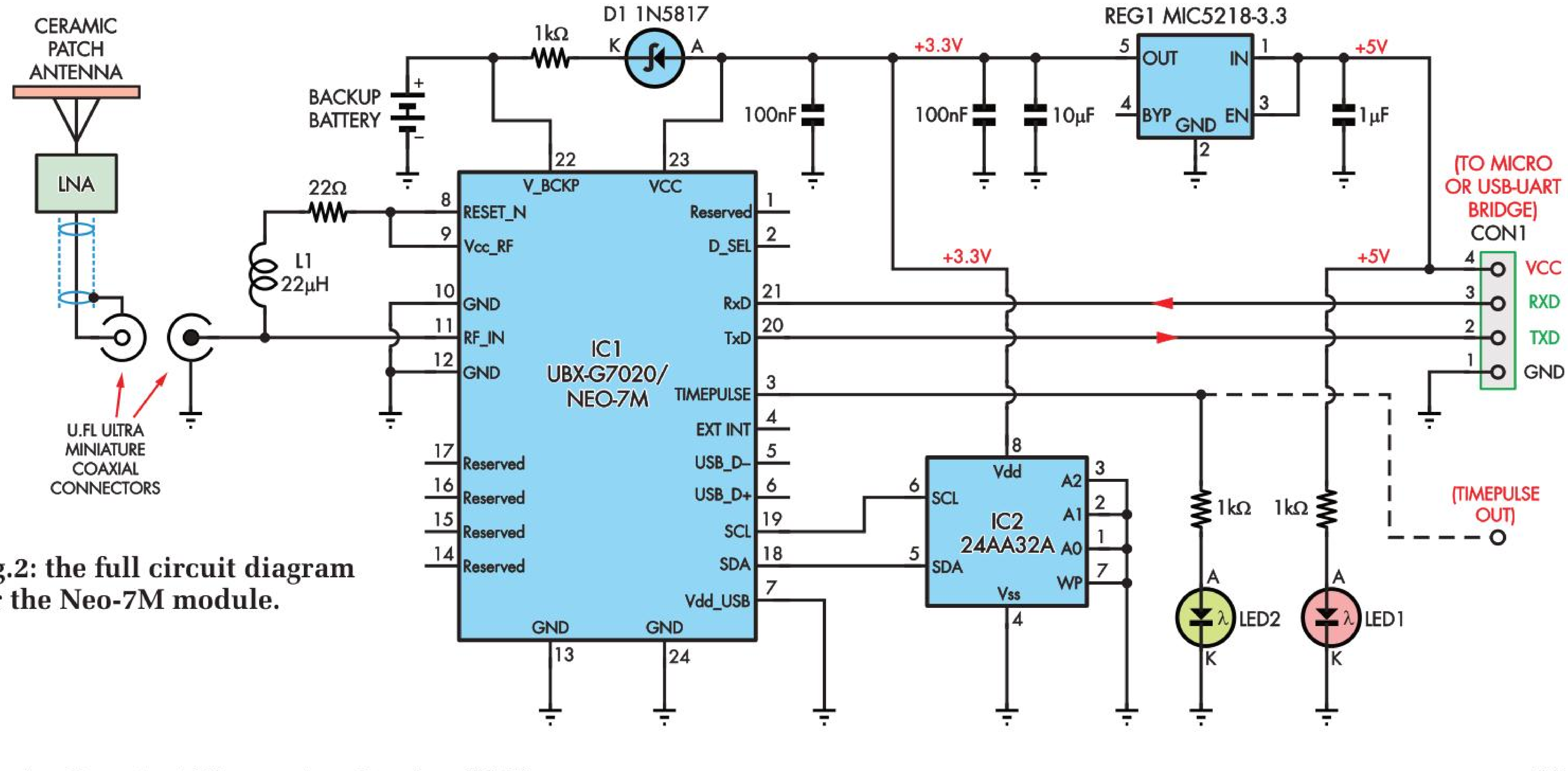
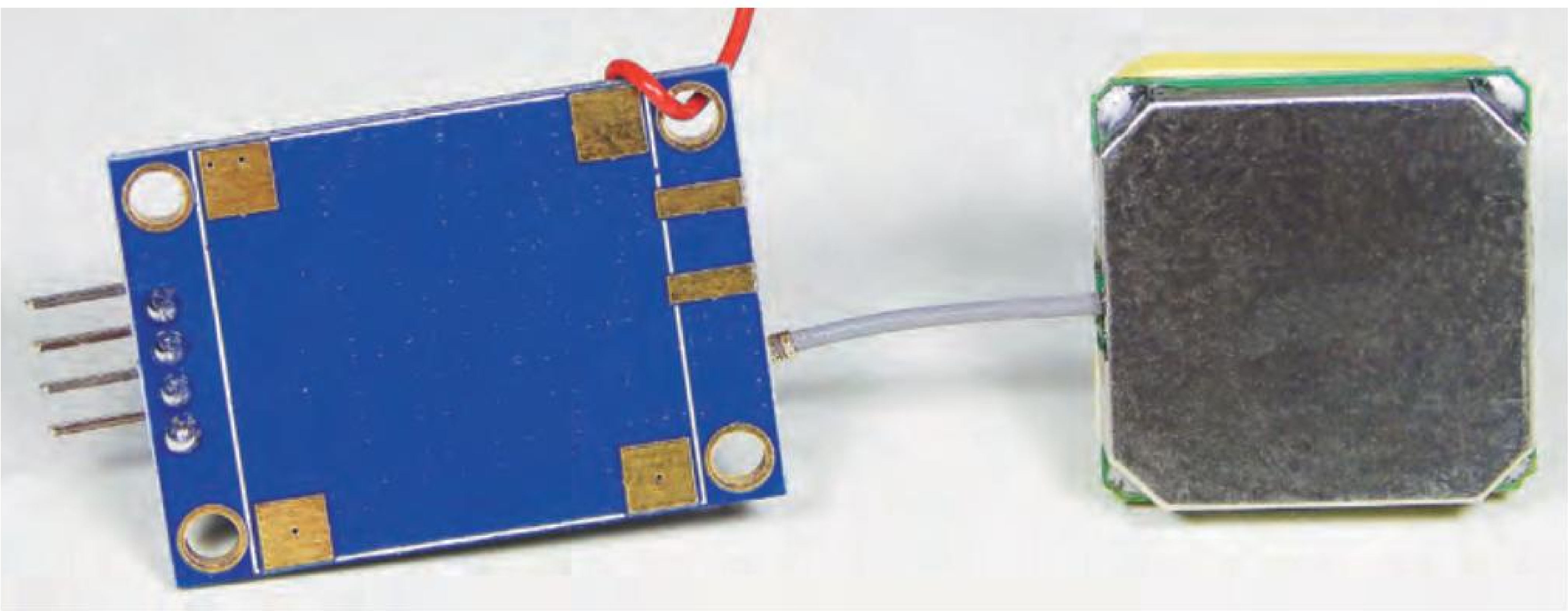

CERAMIC PATCH ANTENNA
LNA
U.FL ULTRA MINIATURE COAXIAL CONNECTORS
BACKUP BATTERY
22Ω
L1 22µH
1kΩ
D1 1N5817
K
A
100nF
+3.3V
REG1 MIC5218-3.3
OUT
IN
BYP
GND
EN
100nF
10µF
1µF
+5V
IC1 UBX-G7020/ NEO-7M
V_BCKP
VCC
RESET_N
Vcc_RF
GND
RF_IN
GND
Reserved
D_SEL
RxD
TxD
TIMEPULSE
EXT INT
USB_D–
USB_D+
SCL
SDA
Vdd_USB
Reserved
Reserved
Reserved
Reserved
GND
GND
IC2 24AA32A
Vdd
SCL
SDA
A2
A1
A0
WP
Vss
(TO MICRO OR USB-UART BRIDGE)
CON1
VCC
RXD
TXD
GND
(TIMEPULSE OUT)
1kΩ
1kΩ
LED2
LED1

Fig.2: the full circuit diagram for the Neo-7M module.



Underside of the Neo-7M and separate ceramic patch antenna. The outer two gold rectangular pads on the Neo-7M can be used to provide an earth connection, which can be useful if you need an outdoor antenna.

UBX-G7020 has achieved a fix from the GPS satellites. This usually happens less than 30 seconds after applying power, assuming the antenna has a reasonable view of the sky.

Unfortunately, the designers of this module have not provided a specific output on the PCB for taking off the 1pps/time pulse signal for external use. But it's not all that hard to do this yourself, with a small amount of surgery.

All you need do is to identify the PCB track connecting pin 3 of IC1 to the top end of the 1kΩ resistor next to LED2 and then scrape some of the protective lacquer from the top of the track as close as possible to the resistor's mounting pad. Then you need to tin it quickly with your fine-tipped soldering iron, so that you can solder the bared end of a short length of hookup wire to the top of the tinned track.

This isn't quite as simple as it might sound. For a start, the PCB track concerned is only about 0.5mm wide. So you have to do the scraping very carefully and the tinning and soldering as quickly as possible – otherwise the track may detach from the PCB laminate and break off, removing the connection to pin 3 of IC1 altogether.

Can you simply solder the wire to the pad at the outer end of the 1kΩ resistor, to avoid risking damage to the thinner track? Yes, you can, but when I tried this myself the solder joint between the resistor and the pad underneath lifted slightly, breaking the connection to the track for both the resistor and the added wire.

LED2 no longer flashed and there were still no 1pps pulses available via the added wire. When I tried re-soldering things, the original 1kΩ SMD resistor overheated and came off altogether.

So I decided to try re-soldering the 1pps takeoff wire to both the resistor pad and the track to pin 3 of IC1, and then fitting a new 1kΩ (0805) resistor in place of the old one – mounted at an angle, so that its outer end could be soldered to the top of the takeoff wire.

This looks a bit messy, as you can see from the photo, but it does work. You should also be able to see from the photo that I looped the takeoff wire through the PCB mounting hole nearby, to avoid stress on the solder joint when the outer end of the wire is moved around.

I also soldered the end of another short length of hookup wire to the nearest of the three long gold-flashed pads at that end of the PCB, to make another ground connection. This wire was also looped through the PCB mounting hole.

Incidentally, those three long gold-flashed pads at the end of the module's PCB seem to have been provided to allow fitting a PCB edge-mounting SMA socket, for connection of an alternative external active GPS antenna. The two outside pads are connected to PCB ground, while the inner pad is connected to the RF input between the U.FL connector and pin 11 of IC1.

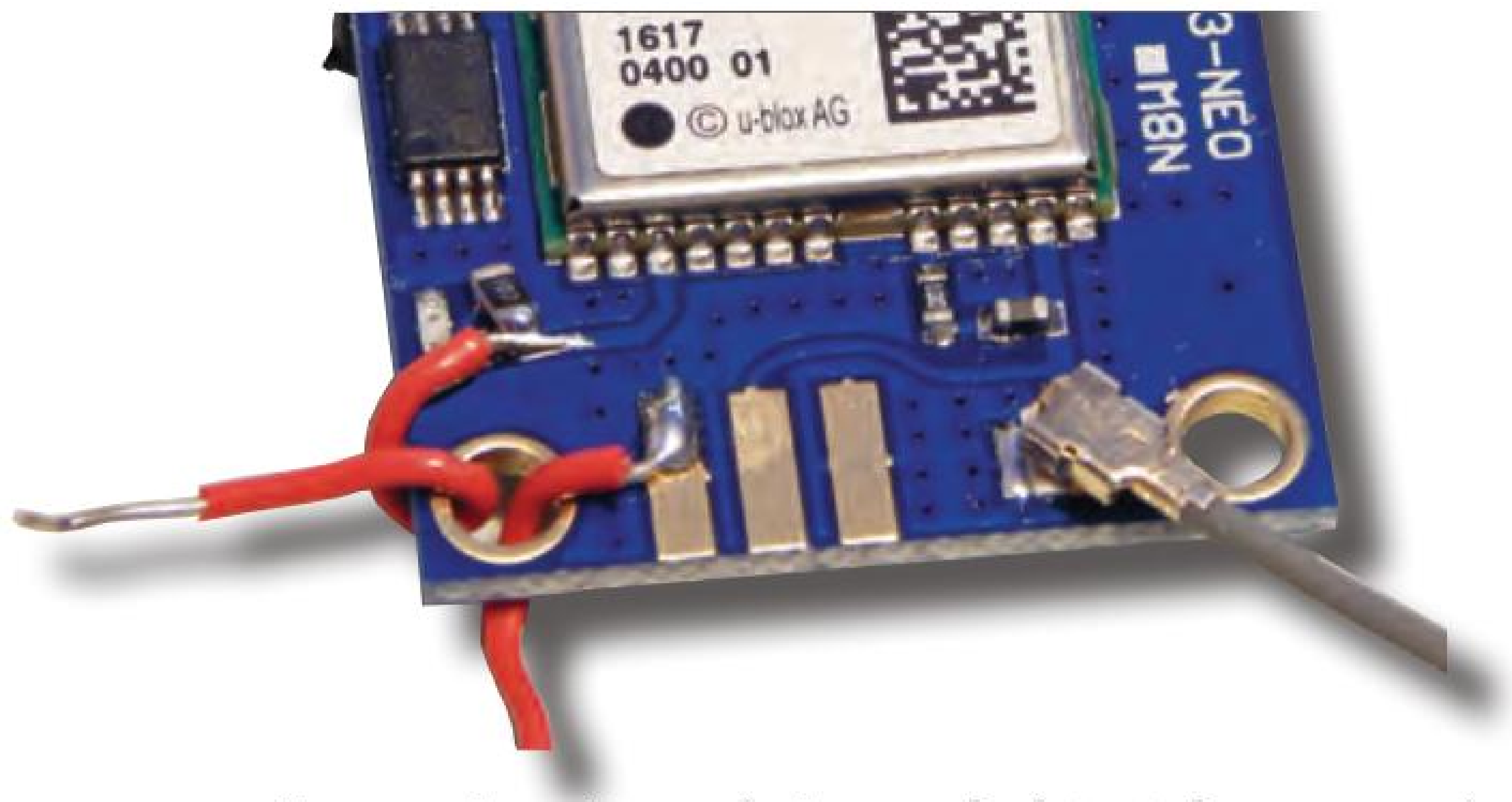
There are also two gold-flashed pads on the underside of the PCB, directly under the two outer pads and connected to ground as well. It's an option that could be handy in applications where you must have an outside antenna.

Inside the VK2828U7G5LF

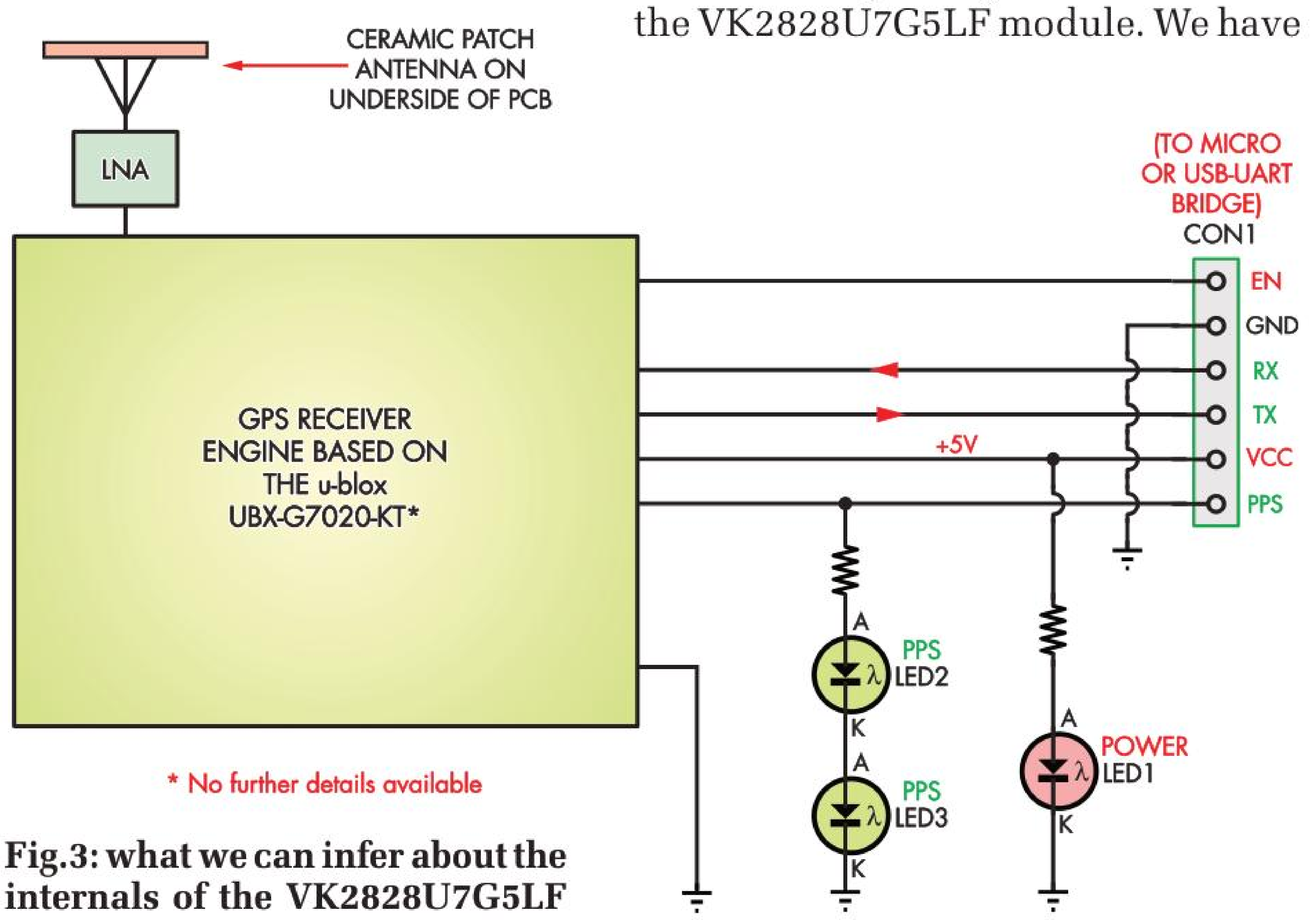
Detailed information regarding the internals of the V.KEL VK2828U7G5LF module is limited. The manufacturer's data doesn't say much at all, apart from confirming that it uses the u-blox UBX-G7020-KT engine chip, giving the pin designations for the module's 6-pin power/IO connector and also giving the overall dimensions of the module as 28 × 28 × 8.6mm.

However, a quick visual inspection of the module when powered up and working revealed another detail: this module provides two PPS indicator LEDs – one on the top of the module's PCB like the red power LED, and the other on the other side of the PCB just at the end of the patch antenna. The module would normally be placed antenna side uppermost for best GPS reception, so this means that this second PPS LED will always be visible – a nice feature.

Fig.3 shows all of the available information regarding the internals of the VK2828U7G5LF module. We have



Some circuit work is needed to take a 1pps/time pulse signal for external use on the Neo-7M. This is done by attaching hookup wire on the PCB track connecting pin 3 of IC1 and the 1kΩ resistor next to LED2. The second hookup wire you can see is attached to one of the gold pads to provide another ground connection.


CERAMIC PATCH ANTENNA ON UNDERSIDE OF PCB
LNA
GPS RECEIVER ENGINE BASED ON THE u-blox UBX-G7020-KT*
(TO MICRO OR USB-UART BRIDGE)
CON1
EN
GND
RX
TX
VCC
PPS
+5V
A
K
λ
PPS
LED2
PPS
LED3
POWER
LED1

* No further details available

Fig.3: what we can infer about the internals of the VK2828U7G5LF module. Note that this module, unlike the Neo-7M, provides a specific output pin for 1pps/time pulse signals.

labelled the two PPS LEDs 'LED2' and 'LED3', since there are no markings on the PCB. One final point which should be noted is that this module does provide a specific output pin for the PPS pulses, so no surgery is required to make use of these pulses.

Putting them to use

It's actually quite easy to make use of either of these GPS receiver modules. As a bare minimum, all you need to do is hook them up to a source of 5V DC and then connect the TX/TXD output to the RXD input of your Arduino, Micromite or other micro, to feed it with the module's NMEA (National Marine Electronics Association) data stream.

Note that with the VK2828U7G5LF module both the E/E$_N$ and V/V$_{CC}$ wires should be connected to +3.3V or +5V, while with the Neo-7M module only the V$_{CC}$ pin (pin 4) is connected to +5V.

To show how easy it is to connect one of these modules to a Micromite, I can refer you to Geoff Graham's article in the August 2017 issue of *EPE* describing his *Touch-Screen Boat Computer with GPS*. There's also quite a bit of information on the web describing how to use this type of module with an Arduino.

It's also surprisingly easy to connect up the module to a PC. All you need is one of the little UART/USB bridge modules, like the one we discussed in the third article in this series (see the March 2018 issue of *EPE*).

As you can see from the diagrams of Figs.4 and 5, you just need to make the correct interconnections between the two modules (note the crossover between the two serial data lines) after which the USB socket on the bridge module can be connected to a USB port on your PC via a standard USB cable.

The nice thing about this approach is that power for both modules comes from the PC via the USB cable, so no separate power supply is needed. In passing, the current drawn from the USB supply by either GPS receiver module plus the UART-USB bridge module combination is only about 60mA.

Remember that when you first plug the cable from the UART/USB bridge into a USB port on your PC, Windows should automatically install the correct VCP (virtual COM port) driver for it. So before proceeding further, it's a good idea to fire up Control Panel and check that the driver has been installed – also noting the COM port number it has been given (eg, COM5 or COM8).

You should now be able to configure the port settings – in this case for communication at 9600 baud, with no handshaking and 8-N-1 (8 data bits, no parity and 1 stop bit) data formatting.

Once the simple setup of Fig.4 or Fig.5 is hooked up to your PC and the LEDs on the modules indicate that it's running, you can easily monitor the NMEA data stream coming from the GPS receiver using a serial terminal emulator program like Tera Term.

This is a very stable serial terminal emulator written originally by Japanese software designer T. Teranishi, which has been maintained as free open-source software since 2007 by the Tera Term Project. At the time of writing, the current version is 4.99. You can download it from the following website: **http://bit.ly/2u2RK8g**

When you install Tera Term and first start it up, you'll need to set it up before proceeding. Do this by clicking on the Setup menu, and then on 'Terminal'. Next, in the dialog that appears, set the New-Line Receive mode to AUTO, check that the terminal ID shows as 'VT100' and that the Local echo is **not** selected.

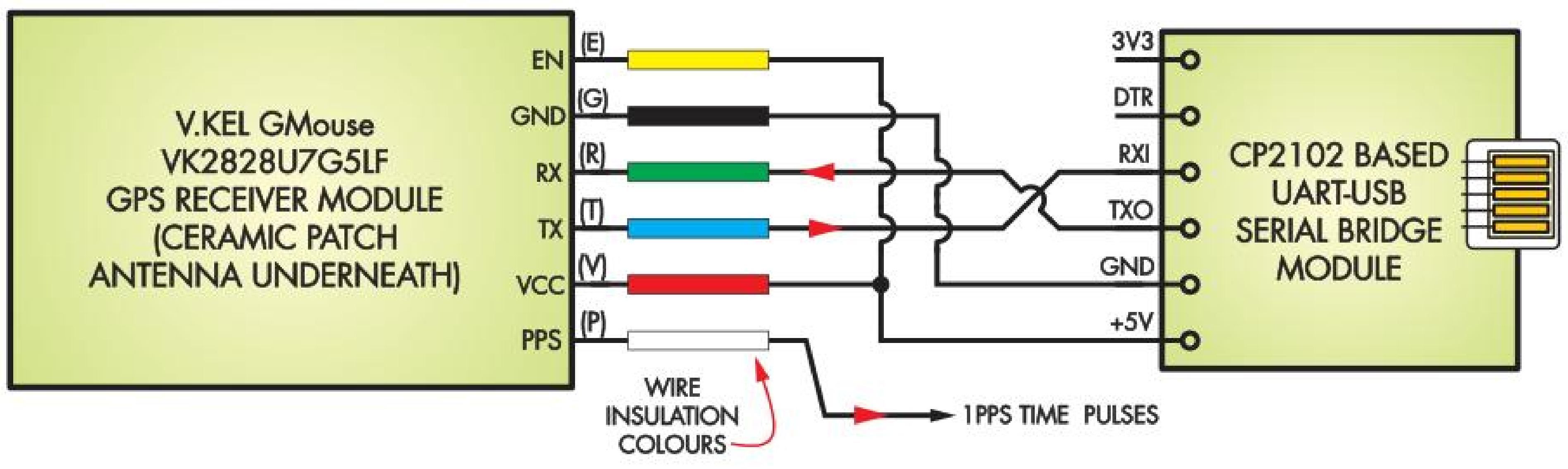
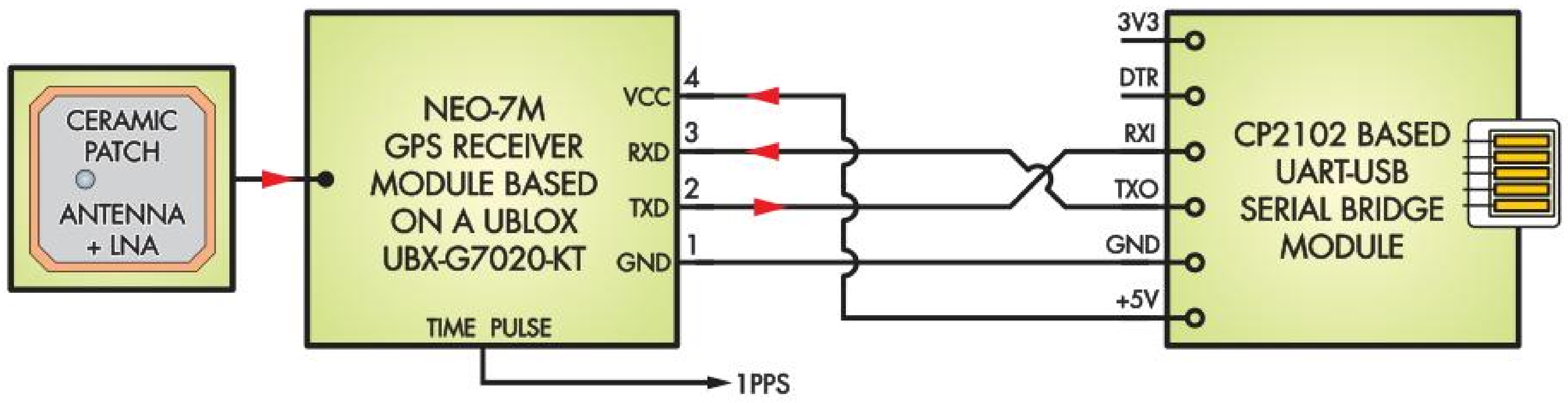


Fig.4 (top): required connections to connect the VK2828U7G5LF to a computer. Fig.5 (bottom): required connections for the Neo-7M to connect to a computer.



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GPS in a Nutshell

GPS or the Global Positioning System was the first global navigation satellite system (GNSS) to become fully operational, in 1995 (the 24th orbiting GPS satellite had been launched in 1994).

GPS was developed by the US Department of Defense (DoD) and was initially intended for use only by the US military, with the signals intentionally degraded for non-military users via a system known as 'Selective Availability'. However, Selective Availability was turned off in May 2000, following a policy directive that had been signed by President Bill Clinton in 1996.

Since then, the uses of GPS by civilians have grown almost exponentially, not just in the US but all around the planet. GPS receivers are now incorporated into mobile phones, laptops and touch-pad PCs, navigation receivers for cars, trucks and buses, tracking systems for trains and light-rail systems and of course navigation receivers for aircraft, ships and boats.

By February 2016, the number of satellites orbiting in the GPS constellation had risen to 32, with 31 of them in use and one a spare in case of a failure. Strictly speaking, only 24 orbiting satellites are needed for navigation anywhere on the globe because this ensures that four satellites are visible at all times. However, the additional satellites provide worthwhile redundancy and improve receiver accuracy.

But how does GPS actually work? Well, all of the GPS satellites orbit the Earth at an altitude of approximately 20,200km, in orbital planes that are tilted at approximately 55° to the equator. They're orbiting at a speed such that they make one full revolution in half a sidereal day (11 hours and 58 minutes). The orbits are arranged so that at least six satellites are always within line-of-sight from virtually anywhere on the planet's surface.

Inside each satellite there are two caesium-beam atomic clocks, and the satellites all make frequent radio contact with each other as well as with dedicated ground monitoring stations. As a result, each satellite always knows two crucial parameters with great accuracy: the current GPS/UTC time and its own current location in terms of latitude, longitude and altitude.

Each satellite also contains a CDMA spread-spectrum microwave transmitter, which continually broadcasts its current time and location data on a number of frequencies – mainly 1.57542GHz (the 'L1' signal) and 1.2276GHz (the 'L2' signal). Although all of the satellites use the same frequencies, the signals from each satellite are encoded with a different high-rate pseudorandom sequence, so receivers can always identify from which satellite any signal is originating.

This allows a GPS receiver to work out its own current location by decoding and comparing each of the signals currently being received from at least four satellites. It does this by measuring the time taken for the signals to come from each satellite, at their specified locations. This allows it to calculate its distance from each satellite, and then to find its own location by finding the intersection of these multiple path distances – a technique called triangulation.

But a GPS receiver doesn't just provide this accurate location information. Most GPS receivers actually provide a continuous stream of many items of data, in a format known as the NMEA 0183 data stream (where NMEA stands for the US National Marine Electronics Association). This emerges from a GPS receiver as alphanumeric serial CSV (comma separated variable) data, usually at a rate of 4800 or 9600 baud (bits/second). It's in the form of a number of one-line message 'sentences', each one identified by a unique header word. All of these header words begin with the characters '$GP', but are then followed by a three-letter combination identifying the type of sentence.

Perhaps the most useful message sentence for many applications is the one carrying the $GPRMC header, also known as the Recommended Minimum sentence. This provides the current UTC time, the receiver's latitude and longitude, its speed in knots (not very useful when operating in a fixed location) and the date.

As well as providing this handy data stream (updated every second), most GPS receivers also provide a 1pps time pulse each second, with its leading edge accurately locked to GPS/UTC time. This makes them especially useful for synchronising clocks and frequency references.

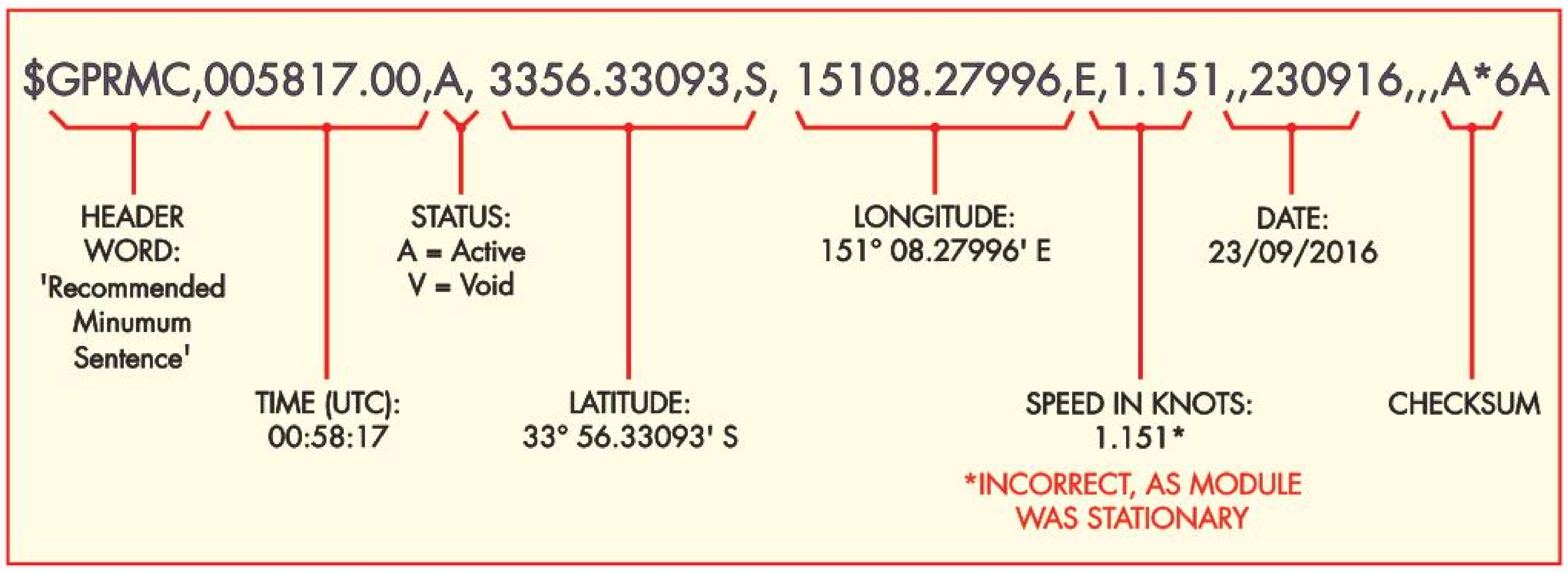

$GPRMC,005817.00,A, 3356.33093,S, 15108.27996,E,1.151,,230916,,,A*6A
HEADER WORD: 'Recommended Minumum Sentence'
STATUS: A = Active V = Void
LONGITUDE: 151° 08.27996' E
DATE: 23/09/2016
TIME (UTC): 00:58:17
LATITUDE: 33° 56.33093' S
SPEED IN KNOTS: 1.151*
*INCORRECT, AS MODULE WAS STATIONARY
CHECKSUM

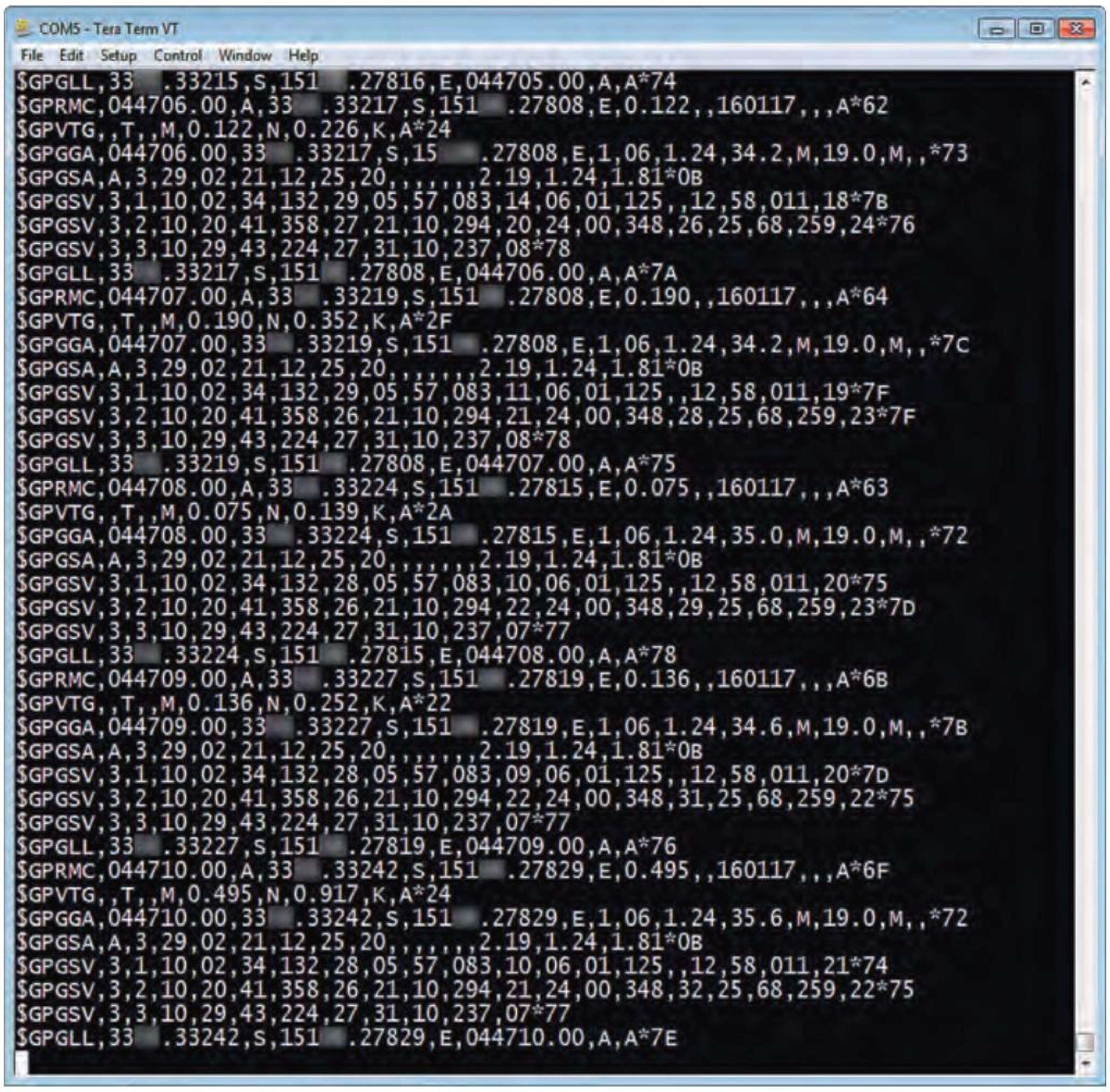
Fig.6: shows the way $GPRMC header data is arranged.

Then exit from the Setup Terminal dialog and click on the Setup menu again, but this time drop down to click on 'Serial Port'. Then in the new dialog that appears, set the Port to the VCP number that you saw in Control Panel and make sure that the data rate is set to 9600 and the format to 8-N-1.

Finally, click on the Setup menu one more time and drop down to click on 'Save setup'. This will let you save the new setup so that in future when you start up Tera Term, it will be able to begin accepting the data stream from your GPS receiver without any further ado.

In fact, as soon as you finish saving the setup, Tera Term should immediately swing into action, receiving the GPS data stream and displaying it in its main window as shown in the adjacent screen grab. Notice that there are quite a few data sentences sent by the GPS receiver each second, as well as the one with the '$GPRMC' header.

Fig.6 shows the way the time, location and date information is arranged



```
$GPGLL,33[redacted].33215,S,151[redacted].27816,E,044705.00,A,A*74
$GPRMC,044706.00,A,33[redacted].33217,S,151[redacted].27808,E,0.122,,160117,,,A*62
$GPVTG,,T,,M,0.122,N,0.226,K,A*24
$GPGGA,044706.00,33[redacted].33217,S,15[redacted].27808,E,1,06,1.24,34.2,M,19.0,M,,*73
$GPGSA,A,3,29,02,21,12,25,20,,,,,,,2.19,1.24,1.81*0B
$GPGSV,3,1,10,02,34,132,29,05,57,083,14,06,01,125,,12,58,011,18*7B
$GPGSV,3,2,10,20,41,358,27,21,10,294,20,24,00,348,26,25,68,259,24*76
$GPGSV,3,3,10,29,43,224,27,31,10,237,08*78
$GPGLL,33[redacted].33217,S,151[redacted].27808,E,044706.00,A,A*7A
$GPRMC,044707.00,A,33[redacted].33219,S,151[redacted].27808,E,0.190,,160117,,,A*64
$GPVTG,,T,,M,0.190,N,0.352,K,A*2F
$GPGGA,044707.00,33[redacted].33219,S,151[redacted].27808,E,1,06,1.24,34.2,M,19.0,M,,*7C
$GPGSA,A,3,29,02,21,12,25,20,,,,,,,2.19,1.24,1.81*0B
$GPGSV,3,1,10,02,34,132,29,05,57,083,11,06,01,125,,12,58,011,19*7F
$GPGSV,3,2,10,20,41,358,26,21,10,294,21,24,00,348,28,25,68,259,23*7F
$GPGSV,3,3,10,29,43,224,27,31,10,237,08*78
$GPGLL,33[redacted].33219,S,151[redacted].27808,E,044707.00,A,A*75
$GPRMC,044708.00,A,33[redacted].33224,S,151[redacted].27815,E,0.075,,160117,,,A*63
$GPVTG,,T,,M,0.075,N,0.139,K,A*2A
$GPGGA,044708.00,33[redacted].33224,S,151[redacted].27815,E,1,06,1.24,35.0,M,19.0,M,,*72
$GPGSA,A,3,29,02,21,12,25,20,,,,,,,2.19,1.24,1.81*0B
$GPGSV,3,1,10,02,34,132,28,05,57,083,10,06,01,125,,12,58,011,20*75
$GPGSV,3,2,10,20,41,358,26,21,10,294,22,24,00,348,29,25,68,259,23*7D
$GPGSV,3,3,10,29,43,224,27,31,10,237,07*77
$GPGLL,33[redacted].33224,S,151[redacted].27815,E,044708.00,A,A*78
$GPRMC,044709.00,A,33[redacted].33227,S,151[redacted].27819,E,0.136,,160117,,,A*6B
$GPVTG,,T,,M,0.136,N,0.252,K,A*22
$GPGGA,044709.00,33[redacted].33227,S,151[redacted].27819,E,1,06,1.24,34.6,M,19.0,M,,*7B
$GPGSA,A,3,29,02,21,12,25,20,,,,,,,2.19,1.24,1.81*0B
$GPGSV,3,1,10,02,34,132,28,05,57,083,09,06,01,125,,12,58,011,20*7D
$GPGSV,3,2,10,20,41,358,26,21,10,294,22,24,00,348,31,25,68,259,22*75
$GPGSV,3,3,10,29,43,224,27,31,10,237,07*77
$GPGLL,33[redacted].33227,S,151[redacted].27819,E,044709.00,A,A*76
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$GPVTG,,T,,M,0.495,N,0.917,K,A*24
$GPGGA,044710.00,33[redacted].33242,S,151[redacted].27829,E,1,06,1.24,35.6,M,19.0,M,,*72
$GPGSA,A,3,29,02,21,12,25,20,,,,,,,2.19,1.24,1.81*0B
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$GPGSV,3,2,10,20,41,358,26,21,10,294,21,24,00,348,32,25,68,259,22*75
$GPGSV,3,3,10,29,43,224,27,31,10,237,07*77
$GPGLL,33[redacted].33242,S,151[redacted].27829,E,044710.00,A,A*7E
```

Data stream from the GPS receiver being viewed in Tera Term.

in the $GPRMC sentences. This should be enough for many people, but if you need to analyse any of the other sentences you can get a lot of useful information by using this link: **www.gpsinformation.org/dale/nmea.htm**

The UBX-G7020-KT GPS receiver chip used in both modules can be programmed to change various parameters in its NMEA 0183 output stream – for example, to select or deselect any of the data sentences, change the data rate from the default 9600 baud and so on. It can also be instructed to change the PPS rate from the default 1pps up to 10pps. All of these changes are made by sending a hexadecimal data stream to the chip via the RX/RXD serial input. This is explained in the VK2828U7G5LF data sheet.

I hope this article gives you enough insight into either of the GPS receiver modules based on the u-blox UBX-G7020-KT chip, so that you'll be confident in getting one and trying it out.

In closing, perhaps I should mention that you don't even have to hook up the receiver modules to a UART-USB bridge module as per Figs.4 and 5 in order to use it purely for extracting 1pps pulses from the GPS signals to drive a digital clock or a GPS-disciplined frequency reference. All you'll need to do is connect the module's V_{CC} (or V_{CC} and E_N) and GND lines to a source of 5V DC, and away it will go.

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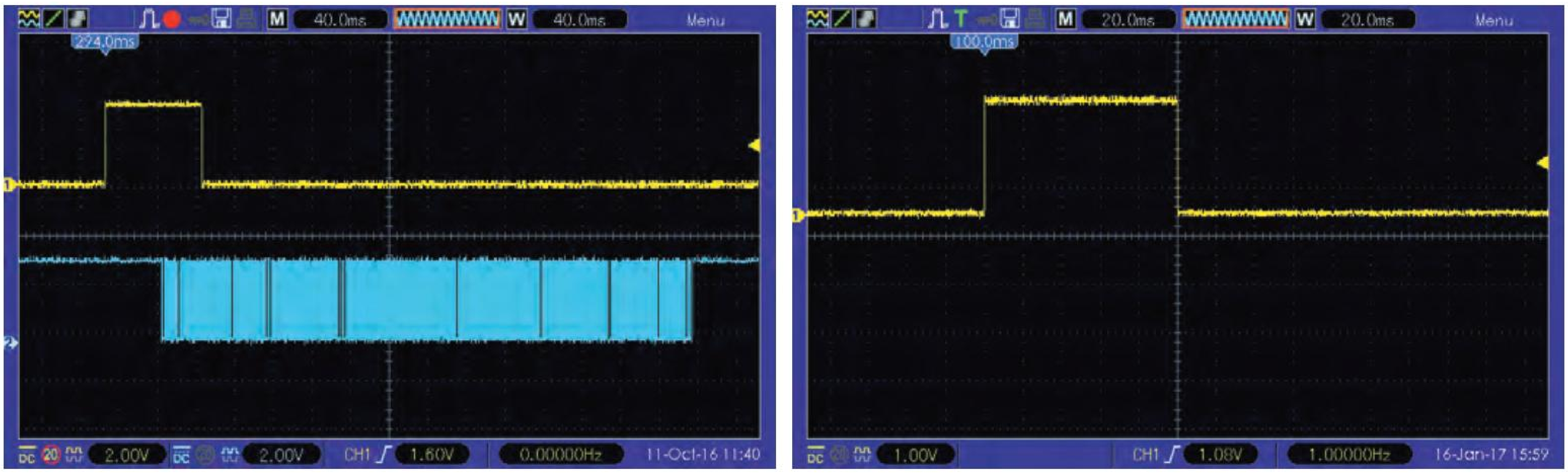

The left plot shows the 1pps pulse and NMEA (National Marine Electronics Association) data from the Neo-7M, while the right plot shows just the 1pps pulse data from the VK2828U7G5LF.

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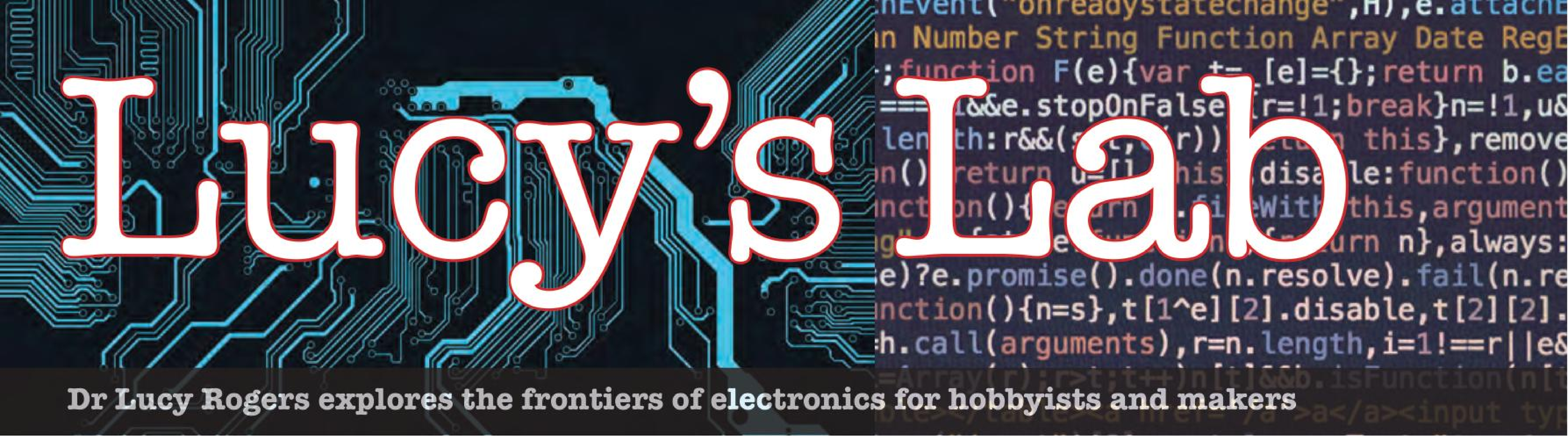

Lucy's Lab

Dr Lucy Rogers explores the frontiers of electronics for hobbyists and makers

The very serious business of play

I love to play. Like most children, I starting playing when I was quite young and it was actively encouraged when I went to playschool. There were sandpits and Play-Doh and dressing up boxes and paints and Lego. We were encouraged to create, to make, to imagine. I remember story time, sitting cross-legged on the carpet looking up in awe at the teacher. She took us off into worlds of adventure, fantasy or just plain silliness.

Less play

Then, as I got older, playtime reduced. I learnt facts and methods – the correct way of doing things. We were allowed to 'create' in art and in story writing, but at secondary school, for me, all play and creativity stopped. We had to analyse, interpret, copy. Squeeze our imaginations to fit into pre-defined boxes that could be examined. There was no time for play.

But outside of the school timetable, I still played and made things. I joined the pottery club, I did woodwork, I made friendship bracelets and puppets. At Christmas I drilled holes in logs, stuck fir-cones on them and sold them as candleholders.

In my home it was normal to make things. My Dad had been an apprentice carpenter, my Mum a florist. We had the 'make do and mend' mentality. I wore hand-knitted jumpers, my clothes had patches on them where I'd ripped them – generally from climbing trees. We fixed things. We made toys, dens, bows and arrows. We used our imagination.

Play leads to engineering...

By the time I did my exams, the time I spent playing and making reduced – 'Plenty of time to play after you have passed your exams' went the refrain.

I was good at exams, but after I completed some, there always seemed to be more. And if you were good at exams, you got less time to make things. The kids that didn't do so well with exams did more practical stuff, and I did less.

I did keep going to the out-of-timetable clubs. Such as *The Great Egg Race Club* – based on a popular 1980s TV show that challenged teams to move an egg from A to B without touching it. My physics teacher would let us loose in the lab and give us challenges. The one that sticks in my mind the most was: 'set a party popper off at the other end of the room'. I attached some weights to the party popper string, and balanced the weights on a stack of polystyrene cups. I intended to hit the cups with a ticker-tape-timer trolley – usually used for measuring acceleration. To make sure I had everything set up correctly, I moved the weights on to a stool. I went to the other end of the room, launched the trolley down a ramp, and watched as it veered off to the side – and hit the stool – knocking the weights off. The party popper exploded. Right under the nose of the teacher, who was doing some marking. He looked up, 'Lucy,' he said, 'you may like to study engineering.'

...but engineering doesn't always lead to play

I went to university to study mechatronics – mechanical and electrical engineering. However, I didn't get on with the electronics or computing. It didn't click with me. I couldn't get a handle on the computer language – we were meant to learn Ada. So I concentrated on mechanical and manufacturing.

The syllabus meant we learnt a lot of facts figures and methods, but there wasn't much creativity involved.

I was sponsored by Rolls Royce – which meant I got to spend three months in different departments – for example, purchasing, sales, R&D and installation. I liked R&D best – research and development – but the job I ended up with was uninteresting and coincided with a period accompanied by a lot of redundancies, so I looked for a new role.

Doctor of bubbleology

I got a job with a small company called CounterFire Limited. I was in the research department. In fact, I *was* the research department. The company made fire-fighting equipment. They knew that a piece of kit made foam – but they didn't know quite how it did it and hence couldn't refine it. So I made clear plastic nozzles and filmed my experiments with a high-speed video camera (this was in the days of VHS tapes – the whole thing filled the back of an estate car, but nowadays it'll fit on my lap!). I spent days and days watching bubbles forming, and since the company had links to a university it was suggested that I write up my findings and submit them for a PhD. So, I now have a doctorate for playing with bubbles.

Back to playing

I left the company and set up a computer consultancy – it paid well, but there was no time for fun, there was no time to play, there was no time to create. In 2011, I looked back over the previous five years. There was nothing that stood out. Nothing memorable. Nothing creative. Nothing fun. It hadn't been 'bad' but there was no 'great' either.

So I escaped and resigned from the consultancy. I started to look around at what I had enjoyed when I was younger, and realised that it was 'making'.

I started to make again, I started to play. The Raspberry Pi computer came out in early 2012 and helped me get over my dislike of computing and electronics. I had great friends who mentored me. I got more and more into connecting physical things to the Internet. But instead of making useful stuff for the Internet of Things, I had fun and I made the Internet of Tat. Silly things, fun things, irreverent things. (Some of which you can see at: **lucyrogers.com**).

I am fortunate that I can now choose to make fun stuff for a living. I get to play – all day!

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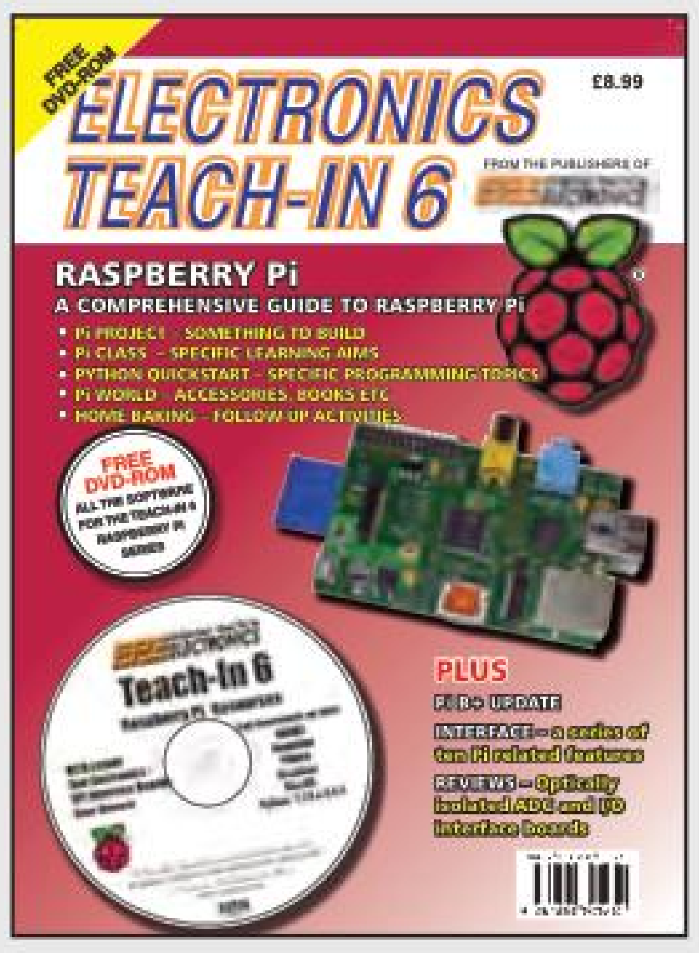

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PIC n' Mix

Mike O'Keeffe

Our periodic column for PIC programming enlightenment

PICMeter Part 2 – Adding the display and some software

WE return to the *PICMeter* this month with *Part 2* of the series. Last month, we implemented a method to measure a range of voltages beyond the normal operational voltage of the PIC. Instead of using the physical range of voltage dividers, we discussed a digital potentiometer. Using the device's SPI communication interface we can set a resistance value in the potential divider from 0Ω to 100kΩ in 256 steps. This provides some circuit protection from larger voltages as well as automatic ranging ('auto-ranging') for the input – all with a low component count.

This month, we will continue looking at the digital potentiometer and examine the software to control it. Before that though, there is one important sub-system we need to add: the display. It will be the set-up I mentioned last month, a 2.2-inch TFT SPI 240×320 screen using the ILI9341 display controller, which can be purchased from eBay for around £8. This is an easy-to-use screen and will be very handy when developing other parts of the project.

SPI – the serial peripheral interface

The display is controlled using an SPI bus (serial peripheral interface). SPI is a common short-distance communications interface, similar to I^{2}C (Inter-Integrated Circuit, pronounced 'I 2 C' or 'I squared C'). SPI was originally created by Motorola, while I^{2}C was a Philips design. Both interfaces output a clock signal alongside the serial data signal to communicate between the master device and the slave device(s).

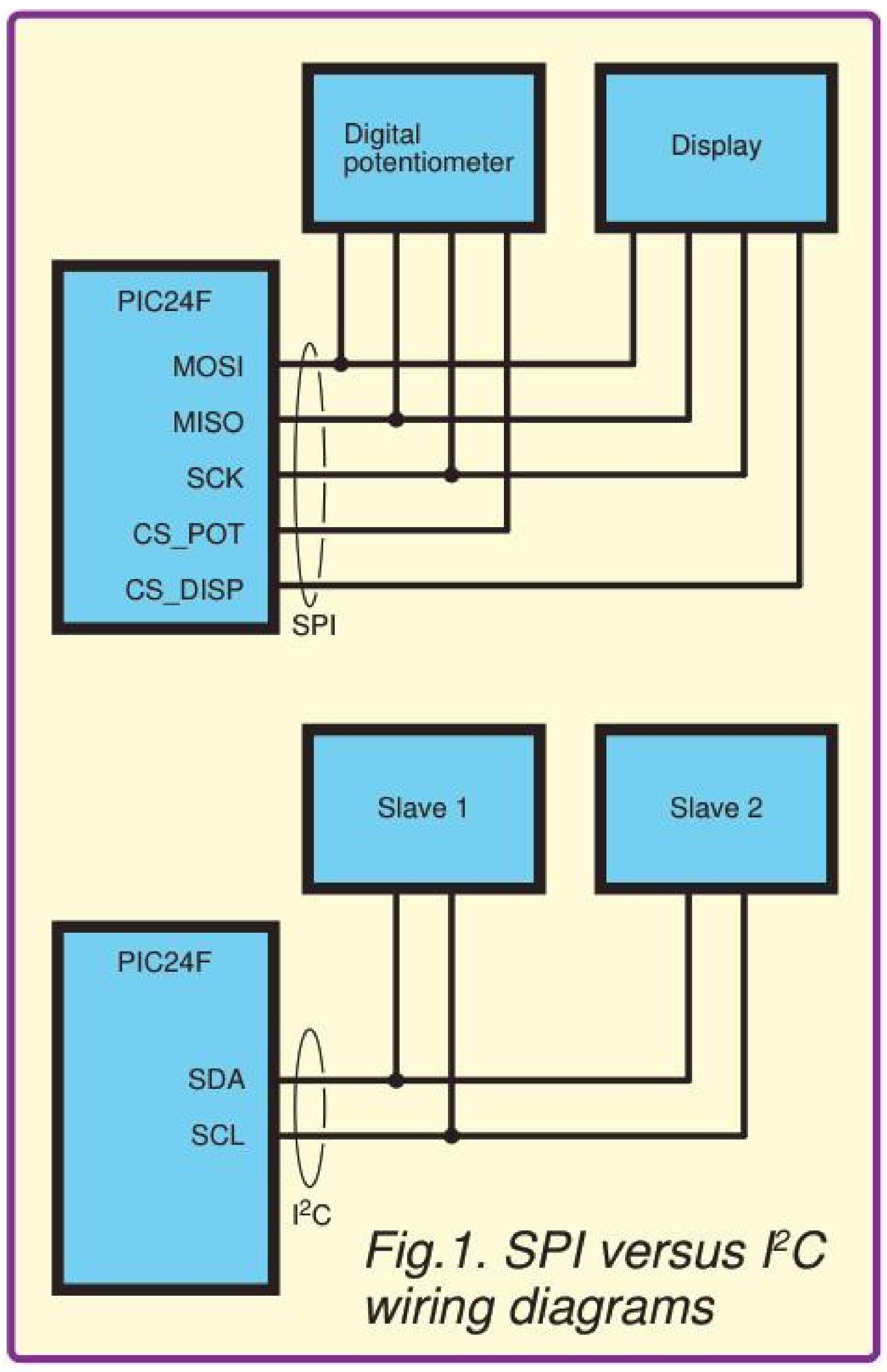


Fig.1. SPI versus I^{2}C wiring diagrams

MODE	CPOL	CPHA
0	0	0
1	0	1
2	1	0
3	1	1

Fig.2. SPI modes

The master device in our case is the PIC24F and the slaves are the display and the digital potentiometer. SPI uses four wires to communicate: MISO, MOSI, $\overline{\text{CS}}$ and SCK. MISO is short for Master In, Slave Out (sometimes referred to as SDI – serial data in); and MOSI is Master Out, Slave In (sometimes referred to as SDO – serial data out). $\overline{\text{CS}}$ is chip select and is active low, and it is sometimes referred to as $\overline{\text{SS}}$ or 'slave select'. SCK is the clock signal, which is controlled by the master.

The MISO, MOSI and SCK signals on the bus are connected to every device. The MISO and MOSI signals allow for full duplex operation (two way communication at the same time). The additional chip select signal is used to select which slave device the master wants to communicate with. This means there is a chip select output for every SPI device on the bus. Fig.1 shows the wiring setup for the SPI bus between the PIC24F, the display and the digital potentiometer.

Fig.1 shows the number of signals and hence connections for the SPI compared to the I^{2}C interfaces. I^{2}C uses only two wires: SDA and SCL, which are the serial data and clock signals. SPI was typically faster than I^{2}C, operating up to 25MHz, but there are new I^{2}C devices on the market that can operate up to 48MHz. However, most I^{2}C devices only operate at 400 kHz. On top of the fact that it can only communicate in one direction at a time (half-duplex). I^{2}C uses device addresses for each device, getting rid of the need for the chip select. This advantage requires extra checking to make sure each device has a unique address.

Back to our *PICMeter*; the PIC24F will control both the display and the digital potentiometer over an SPI interface as these devices don't offer any other methods of control. There are slight differences between the ILI9341 SPI interface and the digital potentiometer. There are four modes of operation for SPI, listed in Fig.2. CPOL is the clock polarity, which indicates what the clock is doing when idle (when nothing is happening) and CPHA is the clock phase, which indicates what edge, the data is clocked on.

The clocking diagrams for each mode are shown in Fig.3. When the $\overline{\text{CS}}$ signal goes low, the device has been selected. The clock (SCK) is either high or low when idle and transitions

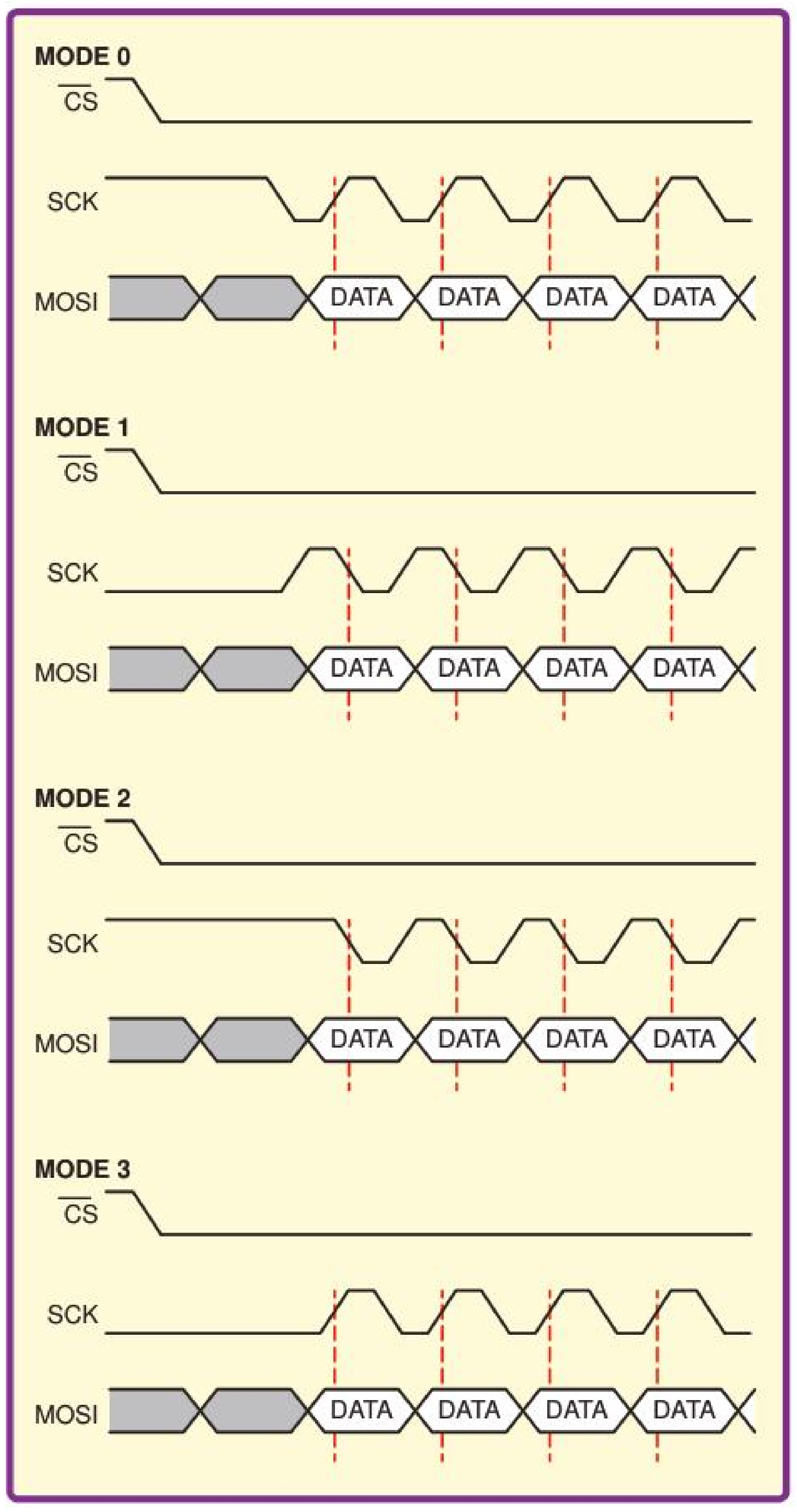
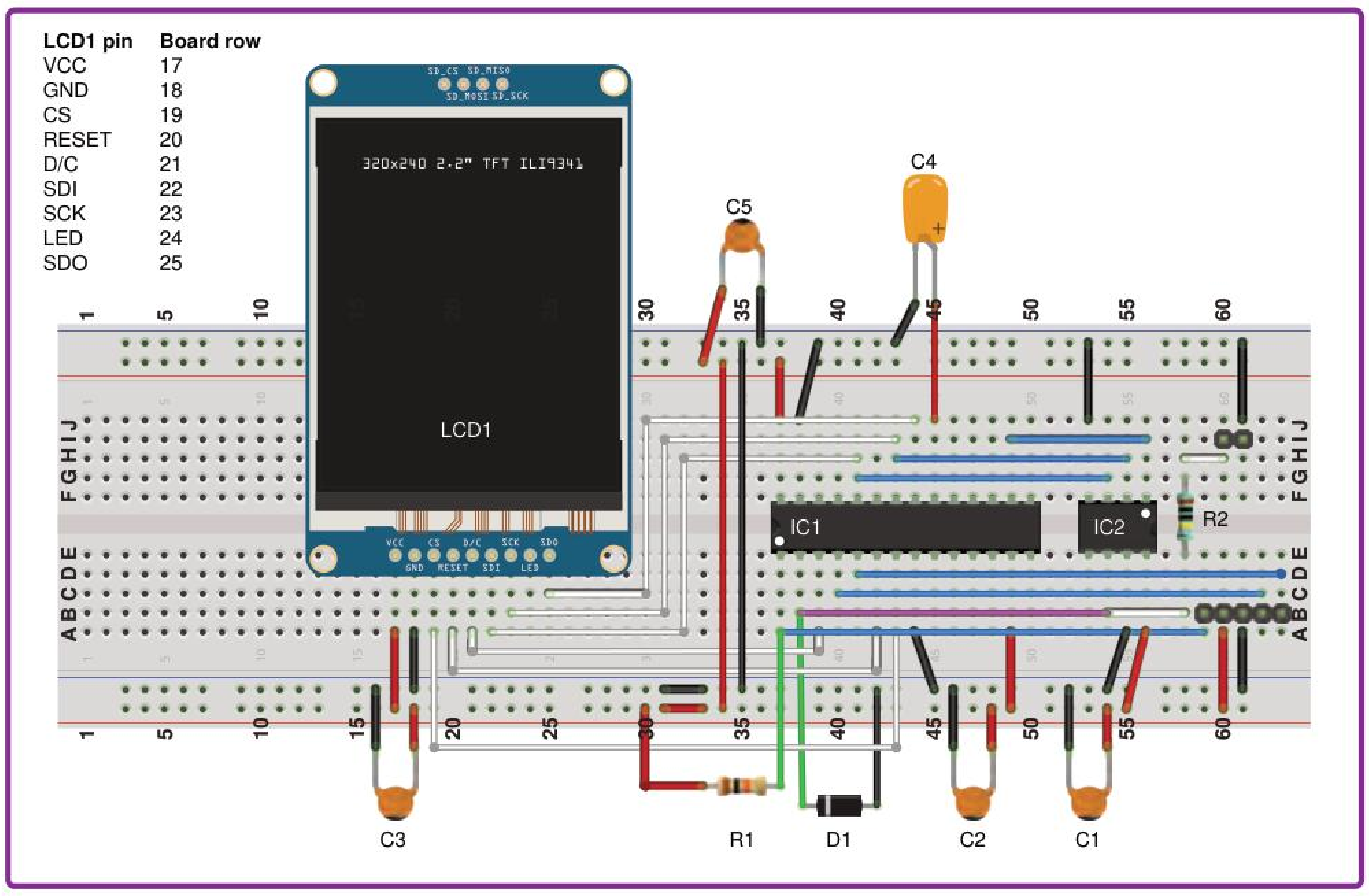


Fig.3. SPI mode timing diagrams



LCD1 pin	Board row
VCC	17
GND	18
CS	19
RESET	20
D/C	21
SDI	22
SCK	23
LED	24
SDO	25

Fig.4. Fritzing diagram of PICMeter

until the data has been transmitted. The data is clocked on either a rising edge or a falling edge, which is indicated by the red line in Fig.3, which shows what's happening with reference to Fig.2. In each mode, the $\overline{CS}$ signal goes low before anything can happen. In mode 0 and mode 2, the SCK signal is idle high (at the beginning when nothing is happening), but in mode 1 and mode 3, the SCK signal is idle low. Further, in Fig.3 we see that the data is clocked on a rising edge for mode 0 and mode 3, while the data is clocked on a falling edge for mode 1 and mode 2.

These modes add options as well as added complexity. A (potential) problem for us is that our screen of choice, the ILI9341, only works in Mode 0, as detailed in the datasheet. Luckily, the digital potentiometer operates in either Mode 0 or Mode 3 and it automatically detects this upon transmission. Due to pin limitations on the digital potentiometer, the serial data input and output are multiplexed. This isn't an issue when only one device is connected, but can potentially cause issues at the PIC24F MOSI output, when the digital potentiometer is trying to drive this signal at the same time as the PIC. The serial data output on the digital potentiometer is only used when a read command is sent. A little workaround is to not use any read commands and de-select the chip when we have finished sending commands.

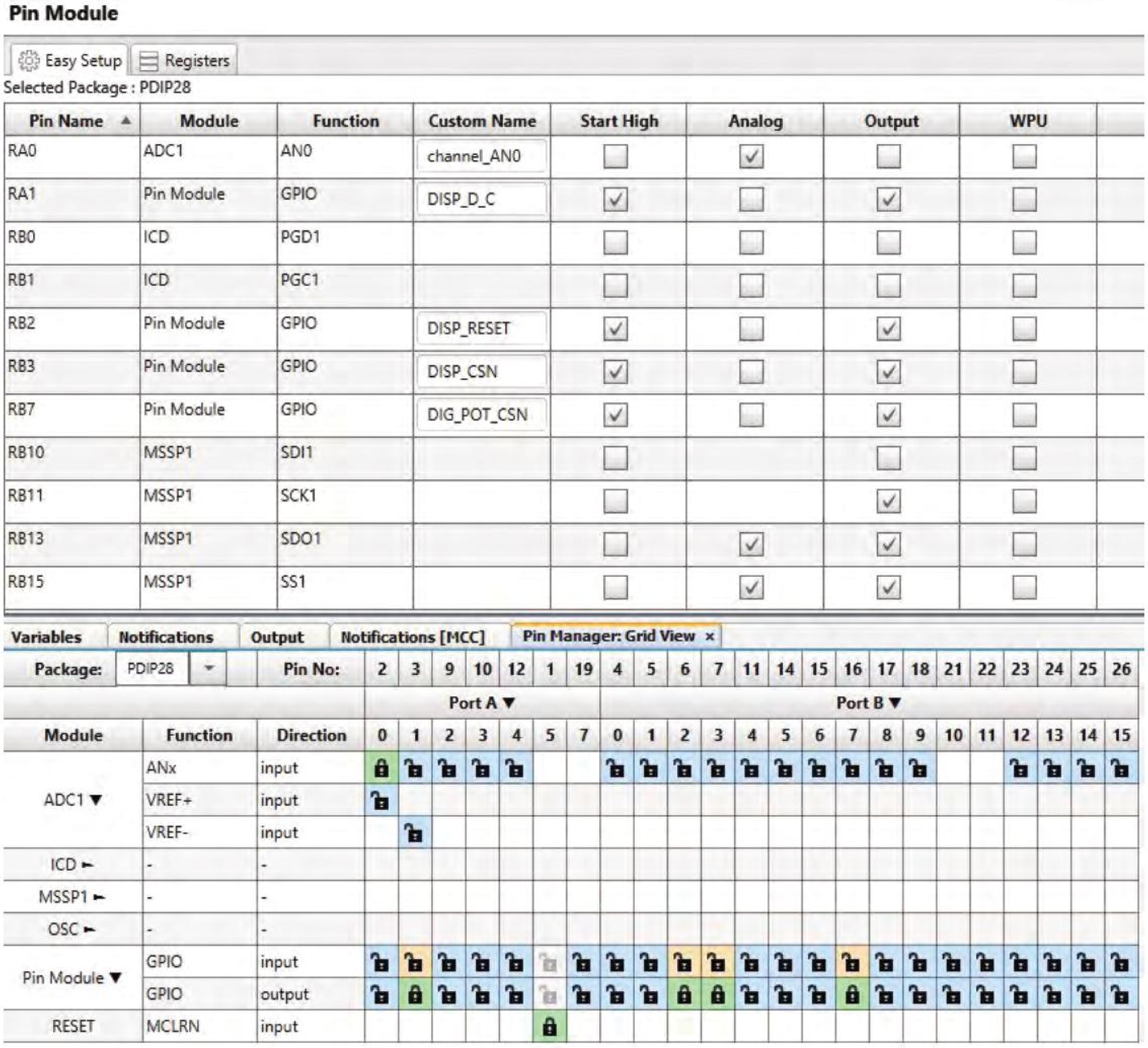
Now that we have a better understanding of the interconnection of our devices, we can connect them all. MISO, MOSI and SCK are connected to both the ILI9341 and the MCP4151. The ILI9341 has its own dedicated chip select, which is only selected when we want to send a command. The MCP4151 also has its own chip select, selecting the device only when we want it. It would be very confusing if both chip selects are enabled at the same time, so let's make sure that doesn't happen. (This is achieved in the software further on.)

The display has a few other connections that need to be wired up. In the Fritzing diagram (Fig.4), we can see V_{CC}, GND, CS, Reset, D/C, SDI, SCK, LED and SDO. V_{CC} is connected to 3.3V (note the display is 3.3V and the PIC24F must be programmed for this voltage, *not* 5V). GND is connected to ground. SDO is connected to our MISO signal on RB10 (note this is the serial data out for the display and master in for the PIC24F). SDI is the MOSI signal connected to RB11. SCK is the clock connected to RB13. LED is a power pin for the backlight, which can be connected directly to 3.3V or you can use a current-limiting resistor to save power by dimming the screen (220Ω works well). This leaves the chip select, reset and D/C pins to be connected. D/C tells the display the mode we want to operate in, either data or command mode. For data mode the D/C signal is high, for command mode it is low. Chip select and reset are then connected to ordinary GPIO inputs, RB3 and RB2.

MPLAB Code Configurator

Instead of manually setting up each port, peripheral and clock, we're going to use Microchip's MPLAB Code Configurator (referred to as MCC onwards). The Code Configurator was covered a few months back (*EPE*, November 2017). It is an additional plugin for the MPLAB X IDE, which automates the setup of internal peripherals, timers, interrupts and GPIOs. The configurator can be installed through the Tools > Plugins menu. Once it is downloaded it can be accessed by either pressing the blue pentagon button in the IDE or in the Window menu in the toolbar.

By using the Pin Module (in MCC), we can set up the basic



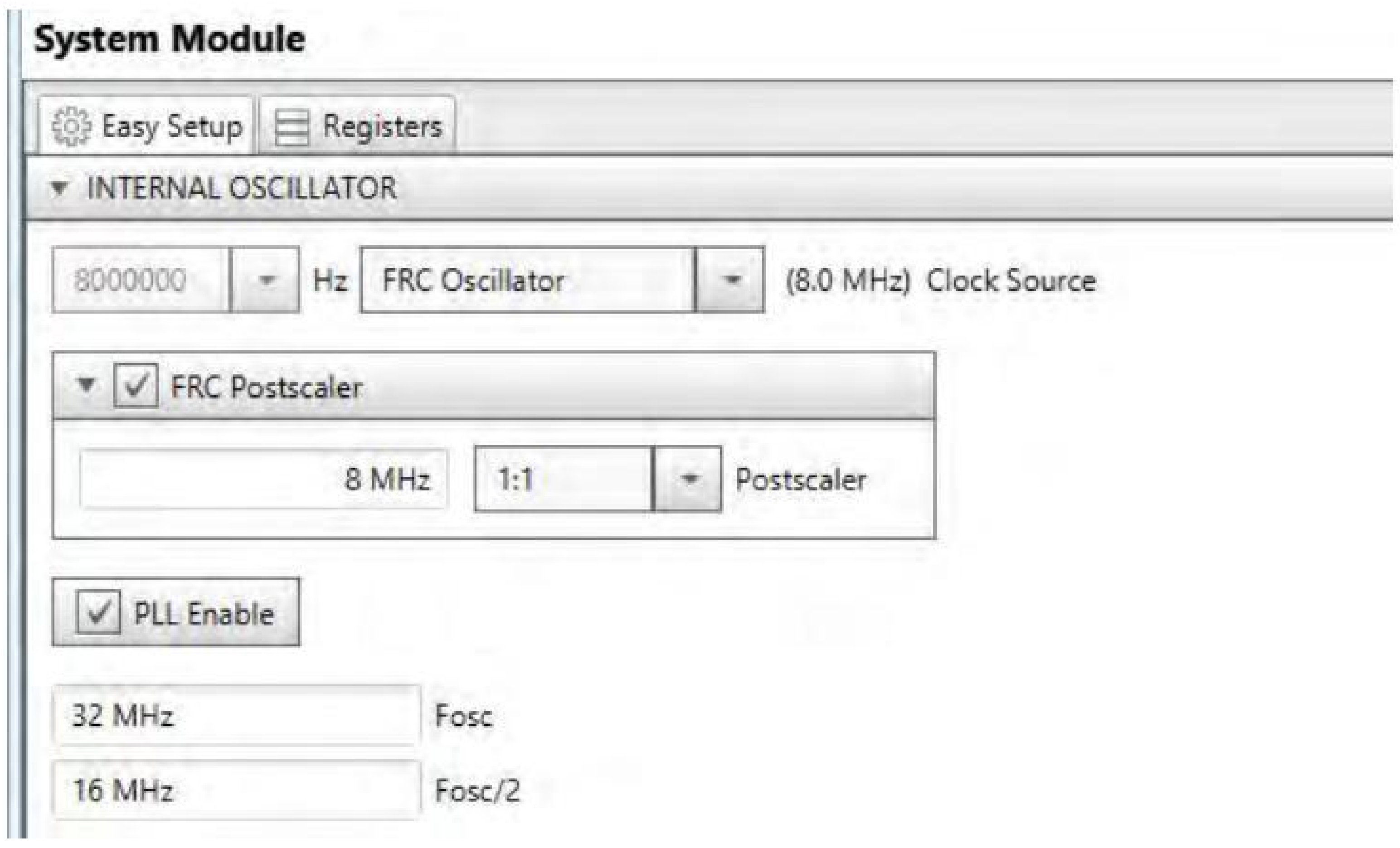
Pin Module

Selected Package : PDIP28

Pin Name ▲	Module	Function	Custom Name	Start High	Analog	Output	WPU
RA0	ADC1	AN0	channel_AN0	☐	☑	☐	☐
RA1	Pin Module	GPIO	DISP_D_C	☑	☐	☑	☐
RB0	ICD	PGD1		☐	☐	☐	☐
RB1	ICD	PGC1		☐	☐	☐	☐
RB2	Pin Module	GPIO	DISP_RESET	☑	☐	☑	☐
RB3	Pin Module	GPIO	DISP_CSN	☑	☐	☑	☐
RB7	Pin Module	GPIO	DIG_POT_CSN	☑	☐	☑	☐
RB10	MSSP1	SDI1		☐		☐	☐
RB11	MSSP1	SCK1		☐		☑	☐
RB13	MSSP1	SDO1		☐	☑	☑	☐
RB15	MSSP1	SS1		☐	☑	☑	☐

Package: PDIP28		Pin No:	2	3	9	10	12	1	19	4	5	6	7	11	14	15	16	17	18	21	22	23	24	25	26
			Port A ▼							Port B ▼															
Module	Function	Direction	0	1	2	3	4	5	7	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
ADC1 ▼	ANx	input	🔒	🔓	🔓	🔓	🔓			🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓			🔓	🔓	🔓	🔓
	VREF+	input	🔓																						
	VREF-	input		🔓																					
ICD ►	-	-																							
MSSP1 ►	-	-																							
OSC ►	-	-																							
Pin Module ▼	GPIO	input	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓
	GPIO	output	🔓	🔒	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔒	🔒	🔓	🔓	🔓	🔒	🔓	🔓	🔓	🔓	🔓	🔓	🔓	🔓
RESET	MCLRN	input						🔒																	

Fig.5. MCC Pin Module window


System Module

▾ INTERNAL OSCILLATOR

8000000 Hz FRC Oscillator (8.0 MHz) Clock Source

▾ ☑ FRC Postscaler

8 MHz 1:1 Postscaler

☑ PLL Enable

32 MHz Fosc

16 MHz Fosc/2

Fig.6. MCC system module window

GPIO pins and give them user-friendly intelligible names. Fig.5 shows the Pin Module setup with the pin manager below. By clicking on any of the blue blocks in the pin manager we can select a pin to be either an input or an output. Green blocks show what has been selected for each pin. Pin RA1 has a green block in the pin manager and has a custom name 'DISP_D_C'. This pin is used for the display to switch between command 'C' and data 'D' modes.

The SPI module is part of the MSSP1 peripherals. It can be added to the project by double clicking on the MSSP and MSSP1 under Device Resources. This adds it to the Peripherals under Project Resources. While we're at it, add the ADC1 peripheral as well. In Fig.5 we see the added MSSP1 peripheral settings.

We control the display through the SPI module. The faster the clock, the faster we can write to the display. The PIC is controlled by a number of clocks that are based off the system clock, referred to as Fosc (oscillator frequency). The Fosc clock can be sourced from a number of options; an external oscillator, internal FRC and a low-power FRC (LPRC). FRC stands for Fast RC (resistor-capacitor) oscillator. It is a low-cost internal oscillator that can be used to minimise component count. The oscillator itself is accurate enough for our application. An external oscillator is typically used when the system clock needs to be more precise, for example asynchronous communications like UART or RTC (real-time clock). The FRC Oscillator is set under System Module under Project Resources (Fig.6). To get the fastest rate for our SPI bus (without using an external oscillator) we can use 8MHz for the FRC Oscillator. If we enable the PLL (phase-locked loop; a method to multiply up the system clock) we can effectively multiply the FRC value by 4 to get 32MHz for the Fosc. The MSSP1 module works from Fosc/2, which is 16MHz, which is the top speed for the SPI bus.

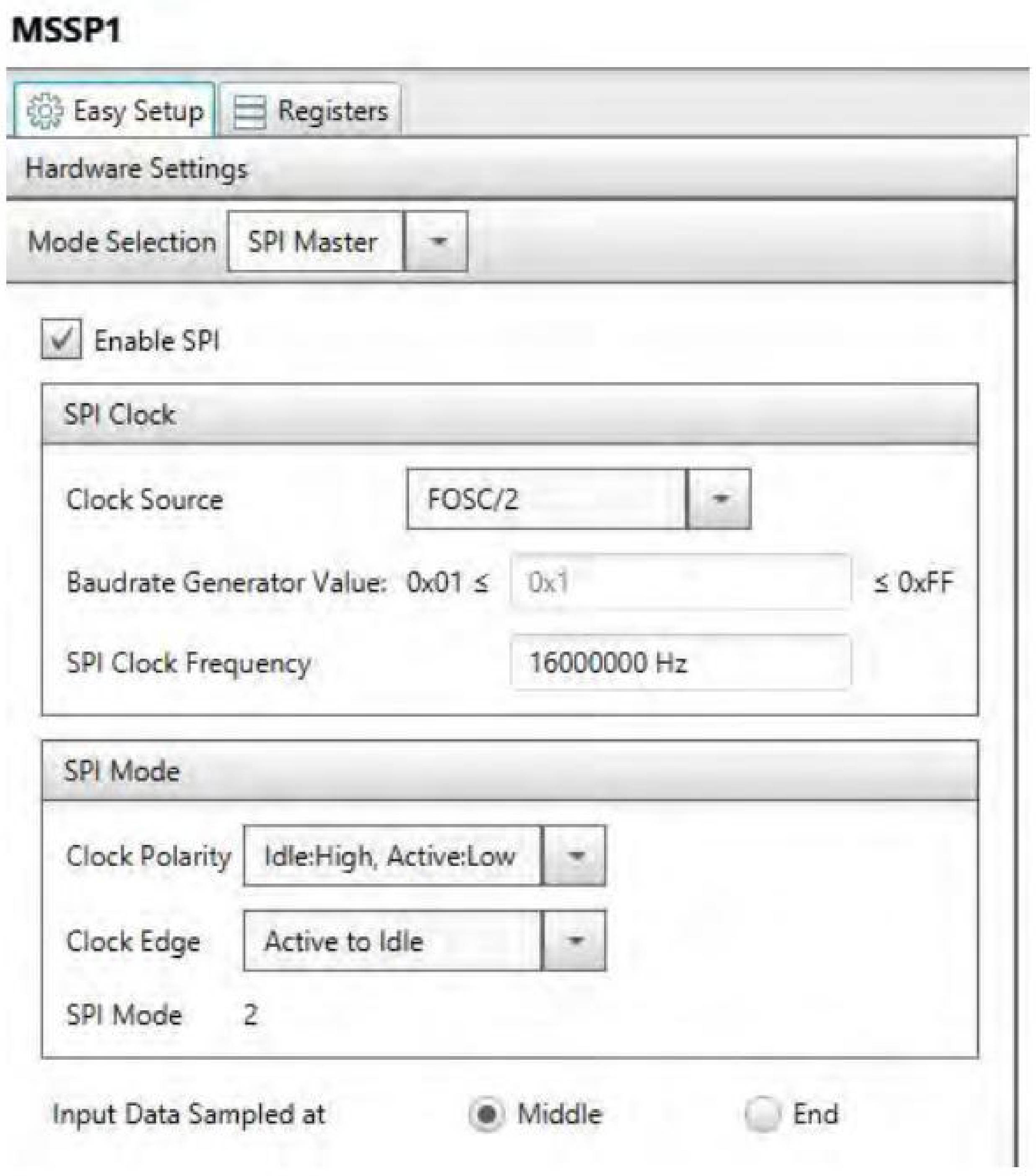
Don't forget we have to select the correct SPI mode to communicate with the display and the digital potentiometer. Fig.7 shows the setup window for the MSSP1. We see here the SPI Clock Frequency is 16000000 Hz, derived from Fosc/2. Under SPI Mode, we want to enable Mode 0. Looking back at Fig.2 we see the clock is high when idle and data is clocked on a rising edge. The Clock Polarity should now be Idle:High, Active:Low and the Clock Edge is Active to Idle.

To finalise the code configurator, click on the Generate button. This automatically creates a number of functions that can be easily used to access peripherals and GPIOs. Each peripheral is automatically initialised in the `SYSTEM_Initialize()` function in **main.c**

The code

We've wired up the display and the digital potentiometer and everything should now be connected. MPLAB Code Configurator has built the basics of our code, so we should be ready to go. Now we need to figure out how to communicate with the digital potentiometer and the display.

Let's start off with the digital potentiometer, which is a little easier than the display. Using the generated function `MSSP1_SPI_Exchange8bit()` we can easily pass eight bits of data to the potentiometer without having to handle the clock signal or anything else. We are only interested in sending a write command to the digital potentiometer to change the resistance. This is performed with two bytes or 16 bits, broken down as follows:


MSSP1

Hardware Settings

Mode Selection: SPI Master

☑ Enable SPI

SPI Clock

Clock Source: FOSC/2

Baudrate Generator Value: 0x01 ≤ 0x1 ≤ 0xFF

SPI Clock Frequency: 16000000 Hz

SPI Mode

Clock Polarity: Idle:High, Active:Low

Clock Edge: Active to Idle

SPI Mode: 2

Input Data Sampled at ● Middle ○ End

Fig.7. MCC MSSP1 setup window

Address 0, Address 1, Address 2, Address 3, Command 0, Command 1, Data 9, Data 8, Data 7, Data 6, Data 5, Data 4, Data 3, Data 2, Data 1 and Data 0.

The address is where the values are stored that we want to edit. The only value we want to edit is Wiper 0, which sits between P0A and P0B of the digital potentiometer. P0B is connected to ground. As we change the wiper resistance value, the voltage divider we have set up changes the input voltage. The greater the resistance, the larger the voltage, and vice versa. Wiper 0 is found at address '0000'.

The two-bit command tells the potentiometer what we want to do. A write command is '00'. A 9-bit data field is the value of the resistance we want to set. The ninth bit isn't used in this device and the eighth bit is used to access the 256th value, which we don't need to access. The data to be written to the digital potentiometer can be written as two bytes, the first byte consists of the address bits, command bits and the ninth and eighth bits of the data. The second byte consists of the lower eight data bits.

```
void writePot_Value(uint8_t data) {
    uint8_t write_op = 0x00;

    DISP_CSN_SetHigh();
    DIG_POT_CSN_SetLow();
    MSSP1_SPI_Exchange8bit(write_op);
    MSSP1_SPI_Exchange8bit(data);
    __delay_ms(5);
    DIG_POT_CSN_SetHigh();
}
```

The code above shows the main function to change the resistor value in the digital potentiometer. We must make sure that the chip select for the display is not active using `DISP_CSN_SetHigh()`. This function is an automatically generated function made by the configurator. This function name makes it easier to read and understand the code compared to the manual method; `LATB3 = 1`. As a side note, both of these methods are identical once the code has been compiled. Next, we set the chip select for the digital potentiometer low (active). The write command is 0x00 as detailed above, then we send our data value. 0x00 represents 0Ω, and 0x100 represents 100kΩ, giving 256 values to choose from. 0x80 represents the mid-point at around 50kΩ. This is a rough value, but can be calculated as follows: 256 values up to 100,000 means a step size of 390. 0x80 is 128 in decimal and multiplied by 390 gives 49,920Ω, which is very close to 50kΩ. This difference affects our accuracy when we are trying to calculate the incoming unknown voltage.

Unfortunately, the ILI9341 controller for the display is not as straightforward to use as the digital potentiometer. We need to be able to draw lines, write characters to the display, select different colours and more. We'll also need a font look-up table. All of this is quite a significant amount of work, and there is no existing code for the PIC24F. However, fortunately we can leverage a previous project by Mike Hibbett from September 2015 (**LCD-Graphic-ILI9341.c**). The code was written for the PIC18F, and contains a number of functions we can use for this project. We will need to port it over to the PIC24F.

When I did this I was surprised – and pleased – how minor the required modifications were. The original code by Mike manually set up the SPI interface, which the code configurator (MCC) simplifies as we saw earlier. The font file (**LCD-Graphic-Font.h**) doesn't need to be touched at all.

The original code from Mike Hibbett works from two main functions `LCD_WR_DATA(unsigned int data)` and `LCD_WR_REG(unsigned char data)`. Another function called `LCD_Writ_Bus` handles the clock and data signals.

```
void LCD_WR_DATA(unsigned int da) {
LCD_AO=1;
LCD_Writ_Bus(da>>8);
LCD_Writ_Bus(da);
}


void LCD_WR_REG(unsigned char da) {
LCD_AO=0;
LCD_Writ_Bus(da);
}
```

The above code section shows the original code using the `LCD_Writ_bus() function.`

```
void LCD_WR_DATA(unsigned int data) {
DISP_CSN_SetLow();
    DIG_POT_CSN_SetHigh();
DISP_D_C_SetHigh();
MSSP1_SPI_Exchange8bit(data>>8);
MSSP1_SPI_Exchange8bit(data);
DISP_CSN_SetHigh();
}

void LCD_WR_REG(unsigned char data) {
DISP_CSN_SetLow();
DIG_POT_CSN_SetHigh();
DISP_D_C_SetLow();
MSSP1_SPI_Exchange8bit(data);
DISP_CSN_SetHigh();
}
```

The next code is the modified code, swapping `LCD_Writ_Bus` for `MSSP1_SPI_Exchange8bit()`. Now all we have to do is call these functions in our main code to use them. Note that I've also added in the additional chip select controls to ensure we're talking to the right device. As mentioned earlier, we need to make sure the two chip selects are not active at the same time.

```
LCDILI9341Init();
LCD_Clear(BLACK);
POINT_COLOR = RED;
LCD_DrawRectangle(1,1,239,319);
```

This modified code from Mike Hibbett can now be used in `main.c`. Start off by initialising the ILI9341 controller using the `LCDILI9341Init()` function. This sets up the ILI9341 controller by refreshing it, setting up registers and

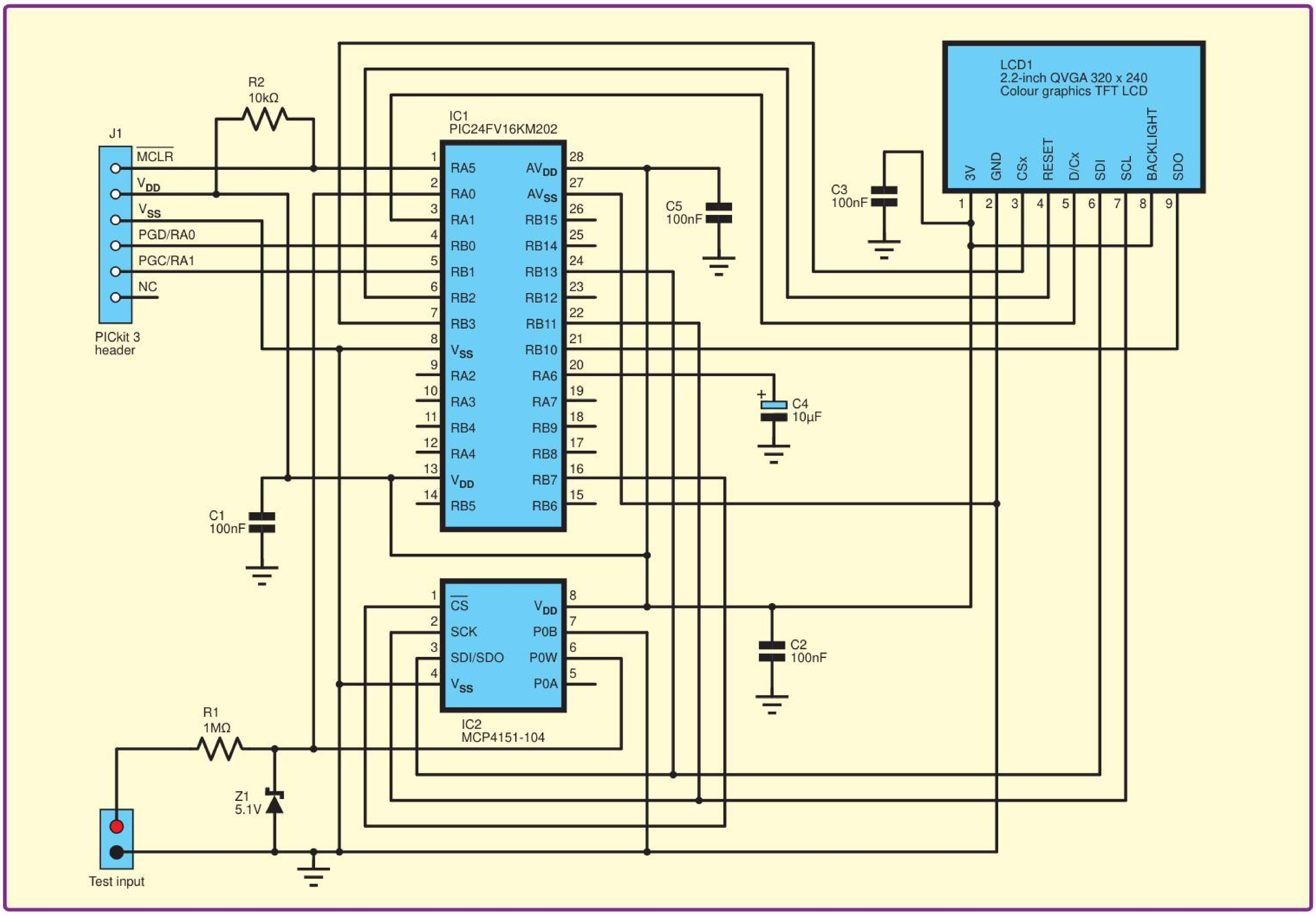

J1
MCLR
VDD
VSS
PGD/RA0
PGC/RA1
NC
PICkit 3 header
R2
10kΩ
IC1
PIC24FV16KM202
RA5
RA0
RA1
RB0
RB1
RB2
RB3
VSS
RA2
RA3
RB4
RA4
VDD
RB5
AVDD
AVSS
RB15
RB14
RB13
RB12
RB11
RB10
RA6
RA7
RB9
RB8
RB7
RB6
1
2
3
4
5
6
7
8
9
10
11
12
13
14
28
27
26
25
24
23
22
21
20
19
18
17
16
15
C5
100nF
C4
10µF
C1
100nF
C3
100nF
LCD1
2.2-inch QVGA 320 x 240
Colour graphics TFT LCD
3V
GND
CSx
RESET
D/Cx
SDI
SCL
BACKLIGHT
SDO
1
2
3
4
5
6
7
8
9
IC2
MCP4151-104
CS
SCK
SDI/SDO
VSS
VDD
P0B
P0W
P0A
1
2
3
4
8
7
6
5
C2
100nF
R1
1MΩ
Z1
5.1V
Test input

Fig.8. Updated PICMeter schematic.

the display orientation. All the registers are detailed in the datasheet (**https://cdn-shop.adafruit.com/datasheets/ILI9341.pdf**). Feel free to peruse them, but it is on the heavy side. On the upside, these are already built into the existing code. `LCD_Clear(BLACK)` fills the screen with black pixels. `POINT_COLOR` sets the colour to be written to the screen for the next command. `LCD_DrawRectangle()` draws a red rectangle around the edge of the screen, framing anything we put in the middle.

```
ADC1_Start();
adc_val = ADC1_ConversionResultGet();
ADC1_Stop();
sprintf(sbuf, “ADC Value: %u”, adc_val);
LCD_ShowString(120,50,sbuf,font_height);
```

Now that the display communication has been covered, let’s get back to our main code. After capturing our ADC value (using the function `ADC1_ConversionResultGet()` built by MCC) , we can then output our value to the screen using `sprintf` to capture a string of characters, then using `LCD_ShowString()` to detail where on the screen we want to place the data.

`sprintf` is a very useful function to use and makes life easier when trying to print a string of characters to the display. There is only one small problem we need to remember when using a microcontroller with limited memory space – the `sprintf` library is beefy! In our piece of code it takes up 8589 bytes of the program data (a fixed area in memory, where our compiled program is stored), of which there is only 16KB. That’s about 50% of our program data, bringing the full project up to 93% of the program data used. For this program, it fit, but it may well limit us when trying to add additional functionality. We’ll return to this again next month and find an alternate route.

Additions to the circuit

It’s important to note some changes to the circuit from last month, which can be seen in the schematics in Fig.8. R1 has changed from 10kΩ to 1MΩ. This increases the voltage range and limits the current drawn from the measured circuit. A 10kΩ pull-up resistor (R2) on $\overline{\text{MCLR}}$ to 3.3V taking the PIC out of reset is necessary. Every power pin on every device should have a 100nF capacitor at the minimum (see C1, C2, C3, C5). VDDCore on the PIC24F, which regulates an internal voltage, needs a 10µF ceramic capacitor (low ESR on C4). I also forgot to connect AVDD (pin 28) and AVSS (pin 27). The updated schematic can be seen in Fig.8.

Additional protection circuits

It’s worth noting I haven’t mentioned much about any protection on the inputs. What happens when a voltage greater than what the *PICMeter* can handle is applied on the input? Adding a reverse-biased Zener diode rated for 5.1V (D1) will sufficiently protect the input pin from over voltages. Our device might be powered from 3.3V, but the pins are 5V tolerant. Zener diode voltage ratings are within 20%, meaning the Zener will start conducting anywhere between 4.08V and 6.12V, which could potentially affect the input. However, 4.08V is sufficiently above 3.3V, meaning our signal should be left alone unless an over-voltage condition happens. The 1MΩ on the input acts as a current-limiting device, which minimises the current draw on the circuit or battery under measurement.

Next month

As we slowly build our project, we find out what works and what doesn’t. All of the code can be downloaded from the *EPE* website. Our design is becoming more and more complex, and I’m not sure how much more we can fit on a bread board. We will have to transition over to a proper PCB soon enough. Next month, we will have a look at how to measure current using a shunt resistor.

Not all of Mike’s technology tinkering and discussions make it to print.

You can follow the rest of it on Twitter at *@MikePOKeeffe*,

on the *EPE Chat Zone* or *EEWeb’s* forums as *‘mikepokeeffe’* and from his blog at *mikepokeeffe.blogspot.com*

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CIRCUIT SURGERY

REGULAR CLINIC

BY IAN BELL

Introduction to Circuit Simulation with LTspice – Part 1

REGULAR readers know that *Circuit Surgery* articles often include the results of circuit simulations, most commonly using LTspice. In fact, we have decided to provide the simulation files described in *Circuit Surgery* via the *EPE* website, starting with last month's differentiator circuit. To help readers who are interested in experimenting with these simulations, or starting to simulate their own designs, this month's topic is an introduction to LTspice (and SPICE simulation in general) and we will continue to look at aspects of using LTspice in future articles.

The origins of SPICE

SPICE was developed in the early 1970s at the University of California, Berkeley, with further significant work in the 1980s. SPICE is notable for being an early example of public domain software, with its source code made available by Berkeley. Back then, the software was distributed for just the cost of the magnetic tapes (remember, this was long before the day of software downloads). Laurence Nagel, working with Prof Donald Pederson, did the original work. This early simulation development has been recognised as having had a very significant impact on electronic engineering, and the IEEE's Donald O. Pederson Award in Solid-State Circuits is named in his honour. Furthermore, it was recently announced that the recipient of the 2019 Award is Laurence Nagel for his development of SPICE as a tool to design and optimise electronic circuits.

SPICE, which stands for 'Simulation Program with Integrated Circuit Emphasis', was developed because integrated circuits require complex fabrication processes and cannot be changed significantly once they were made. Fabricating an IC is also expensive compared with building a circuit with discrete components, so using a simulator to analyse the circuit greatly increases the chance that an IC works correctly first time. SPICE is now the *de facto* industrial standard for computer-aided electronic circuit analysis, and is widely used for both IC and discrete designs. Spice was originally an analogue circuit simulator, but modern versions allow logic gates and more complex digital functions to be included, allowing digital and mixed-signal (analogue and digital) circuits to be simulated. However, SPICE is not normally used for large, fully digital circuits.

SPICE choices

There are many versions available, some of which are free – for example, LTspice. The free versions tend to come from semiconductor manufacturers, where you get simulation models of their ICs as part of the download. This encourages engineers to try their parts and makes provision of the free software worthwhile for the manufacturer. This is exactly the case with LTspice, which is so called because it was developed by Linear Technology (LT), although it was originally called SwitcherCAD because it features optimisations to help simulate their range of switching (power supply) ICs. LT is now part of Analog Devices, which announced the completion of its acquisition of Linear Technology in March 2017. LTspice is not the only free SPICE simulator; there is a free version of TINA from Texas Instruments. There are also free on-line SPICE simulators. These include PartSim (**partsim.com**), which is promoted via EEWeb (**eeweb.com/tools**).

When and how

In discussions of circuit simulation, particularly for analogue circuits, you may hear objections to its use. These fall into two main categories, which could be summed up as: 'do the maths' and 'reality is better'. Both points are relevant to any SPICE simulation, but do not mean that you should reject the idea of simulating your circuits. Simulation is a powerful tool, and all tools can cause you problems if used incorrectly, without proper thought, or without an understanding of their limitations. Before introducing the LTspice software we will consider some of the advantages and issues with using SPICE simulation. It is also worth mentioning that as well as using LTspice for design, simulation can also be a very valuable educational tool for studying circuit theory.

Once you have learnt the basics of how to use a simulator's user interface it can be tempting to just throw circuits at it to see what happens – without having a clear idea of what to expect. The instruction to 'do the maths' serves as a reminder that if you are simulating a circuit then you should have some idea of the theory behind its operation and be able to calculate, at least roughly, values for components, expected operating voltages and currents, and other characteristics. The simulator, using the power of the computer, can crunch far more calculations than the human designer can, giving better accuracy, but only if the simulation is configured correctly in the first place. If you make an error with data entry or simulation set-up, and don't have sufficient understanding then you may believe the erroneous results, with potentially disastrous consequences. The old, computer programming maxim of 'garbage in garbage out' (aka 'GIGO') is well worth keeping in mind whenever running a simulation.

Real-world prototyping

The assertion that 'reality is better' refers to the idea that if you build a physical circuit (prototype) to try out your ideas, then that will provide absolute confidence in the circuit's function and performance. This assumes that prototyping without simulation is feasible, both practically and economically. It may not be, as per commercial designers working on IC designs discussed above. For circuit boards, rather than ICs, the advantage of simulating may be less obvious; however, there are still good reasons for simulating. In the case of amateur designers the financial argument may be applicable – a simulation may save money if it helps you identify exactly the right components to purchase.

A breadboard prototype for a printed circuit board design, or any other prototype which has a different physical structure from the final version, may behave significantly differently. For example, the same amplifier circuit built on both a PCB and solderless breadboard may be stable in one version, but not in the other. Such variations are typically

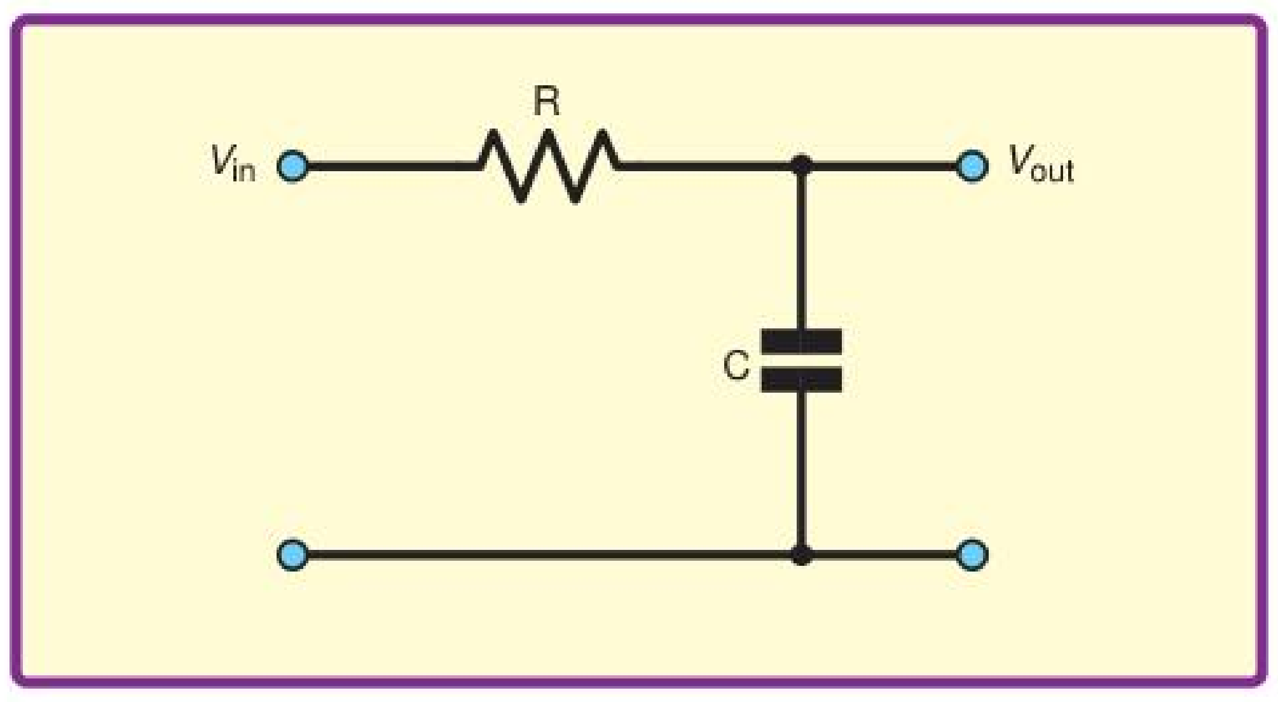


Fig.1. RC circuit to be used as a simulation example.

caused by differences in the parasitic components. Parasitics are the unwanted characteristics of real-world wiring and components – the resistance of tracks, the capacitance of a resistor. This can be accounted for in a simulation, so the simulation *may* be more accurate than a physically different prototype, although this is not necessarily easy to achieve.

Advanced design software (eg, for ICs) is able to automatically extract a lot of parasitic data from a physical description of the design to facilitate more accurate simulation (at least in specific circumstances). This extensive analysis may not be available in all cases, particularly for amateur designers, but with an understanding of the circuit the most likely problems can be identified, and the relevant parastics estimated or obtained from component data sheets. Various online tools can assist here; for example, if you thought that PCB track (trace) resistance might be significant in a design then you could use an online trace resistance tool, such as the one provided by EEWeb to obtain a value for use in simulation (see: **eeweb.com/tools/trace-resistance**).

Another advantage of simulation is the ability to explore the effects of variations in component values and operating conditions. A single prototype may work fine, but if you build several will they all work as well when each individual component is slightly different due to manufacturing tolerances? What happens if the temperature changes, or the supply voltage is slightly different? Simulators can help designers explore these effects without having to build large numbers of prototypes, or run through multiple time-consuming testing scenarios.

Simulators can provide parameter sweeps (simulations with specific values systematically varied), controlled random variation in many values (called a 'Monte Carlo' simulation) and sensitivity analysis (determine which component variations have the largest effect on a given circuit parameter). This does not mean that no prototype should ever be built and thoroughly tested, but it helps make it more likely that the circuits you do go to the trouble and expense of building and testing will meet your requirements. Although amateur designers will rarely need to worry about high yields in mass-produced circuits, exploring the effects of component variation may be useful in some one-off designs, particularly for higher-performance circuits. It can also help inform decisions about component selection.

Do the maths

We will soon describe how to simulate an example circuit in LTspice, but in the spirit of 'do the maths' discussed above, we will first describe and discuss the circuit. Let's look at something simple, familiar and ubiquitous – the *RC* circuit shown in Fig.1. One aspect of the theory related to this circuit tells us that if the capacitor starts uncharged (with $V_{in} = V_{out} = 0V$), and at some point in time we apply a fixed DC voltage to V_{in} then the capacitor will charge through the resistor. V_{out} will vary with the time (t) elapsed since V_{in} was applied, in accordance with the well-known capacitor charging equation:

$$V_{out} = V_{in}\left(1 - e^{-t/RC}\right)$$

The value *RC* is called the 'time constant', and the theory tells us that after a period of four time constants V_{out} will be at about 98% of V_{in}. This gives us some idea of the likely time periods required in a simulation.

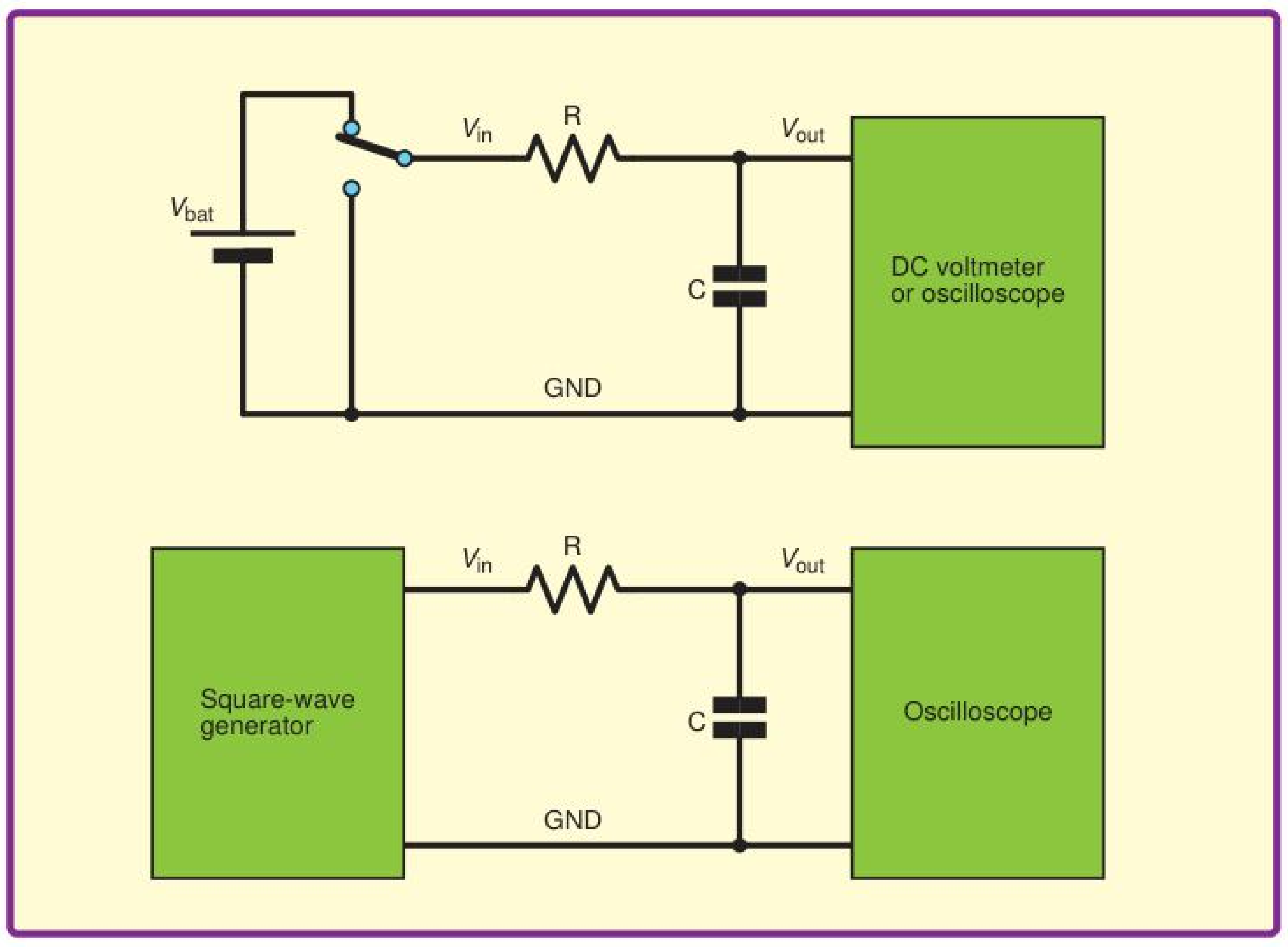


Fig.2. Possible lab set-ups for investigating the time response of the circuit in Fig.1.

Another important characteristic of the circuit in Fig.1 is that if we apply an AC signal then it behaves as a low-pass filter. At very low frequencies the impedance of C is very large – it is more or less an open circuit, so all of V_{in} passes to V_{out}. At very high frequencies the impedance of C is very low – it is more or less a short circuit, so V_{out} will be close to zero. What constitutes 'low' and 'high' frequencies depends on the values of both R and C (again the term RC appears in the equation). A frequency of particular interest is the defined cut-off frequency (f_c), which is given by:

$$f_c = \frac{1}{2\pi RC}$$

At this frequency, the magnitude of V_{out} is $0.707V_{in}$. The AC theory for this circuit indicates the most suitable range of frequencies to simulate and what to expect in terms of output levels.

The schematic in Fig.1 is sufficient to define the circuit we are discussing, but not sufficient for testing in the lab, or for simulation. Specifically, in both cases, we need to define what we are going to do to the circuit's inputs, and what measurements we are going to make. For example, in the lab, if we had an *RC* circuit with a sufficiently long time constant, we might connect the input to a battery via a switch, as shown in Fig.2, and record the voltage against time with a meter and stopwatch. This is clearly very limited and not very accurate – it would be better to use an oscilloscope to capture the waveform, and possibly use a square-wave signal generator to repetitively change V_{in}, rather than using a mechanical switch, but you can only do this if you have the test gear. Simulators can provide or display any values that have been recorded during the simulation, or post-process the data into the form required. Depending on what you choose to do, SPICE effectively provides you with a range of 'virtual' instruments including multimeters, oscilloscopes, spectrum analysers and curve tracers.

The lab set up in Fig.2 is for looking at the timing of the circuit (the charge and discharge waveforms). However, if we want to investigate the AC response we need a different lab set up. We need to apply a sinewave and measure the input and output amplitudes with an AC meter or oscilloscope, as shown in Fig.3. We can then find the gain over a wide range of frequencies by dividing the output by the input.

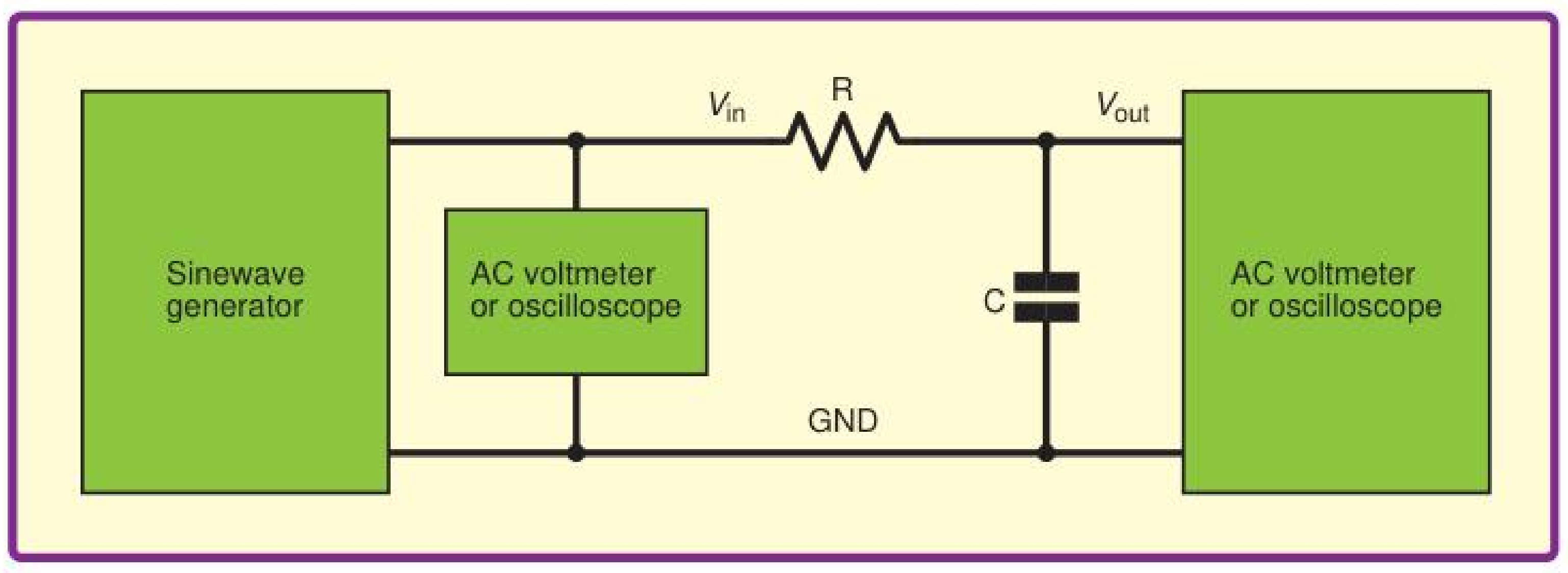


Fig.3. Possible lab set-up for investigating the AC response of the circuit in Fig.1.

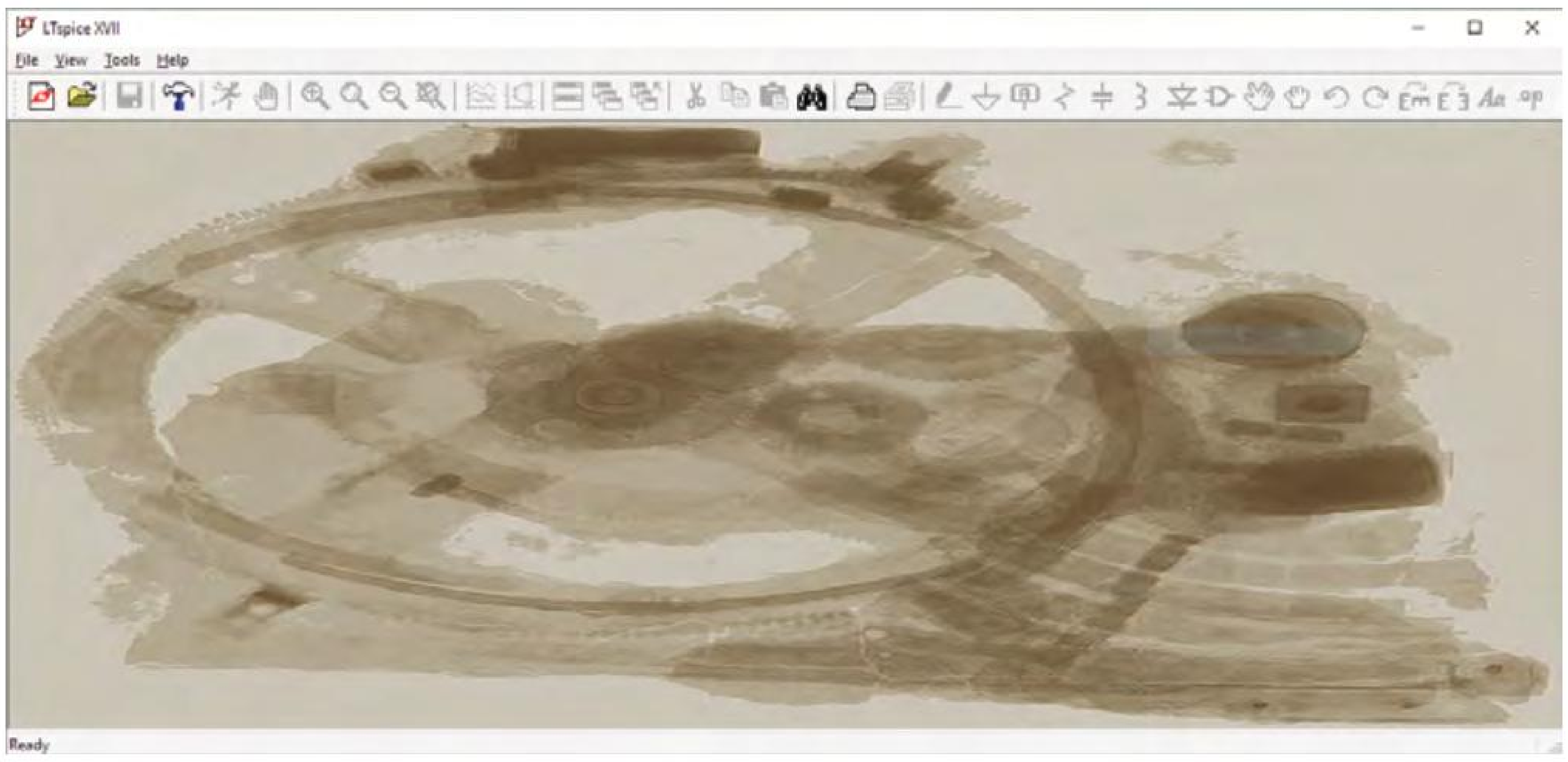


Fig.4. The LTspice application running on Windows.

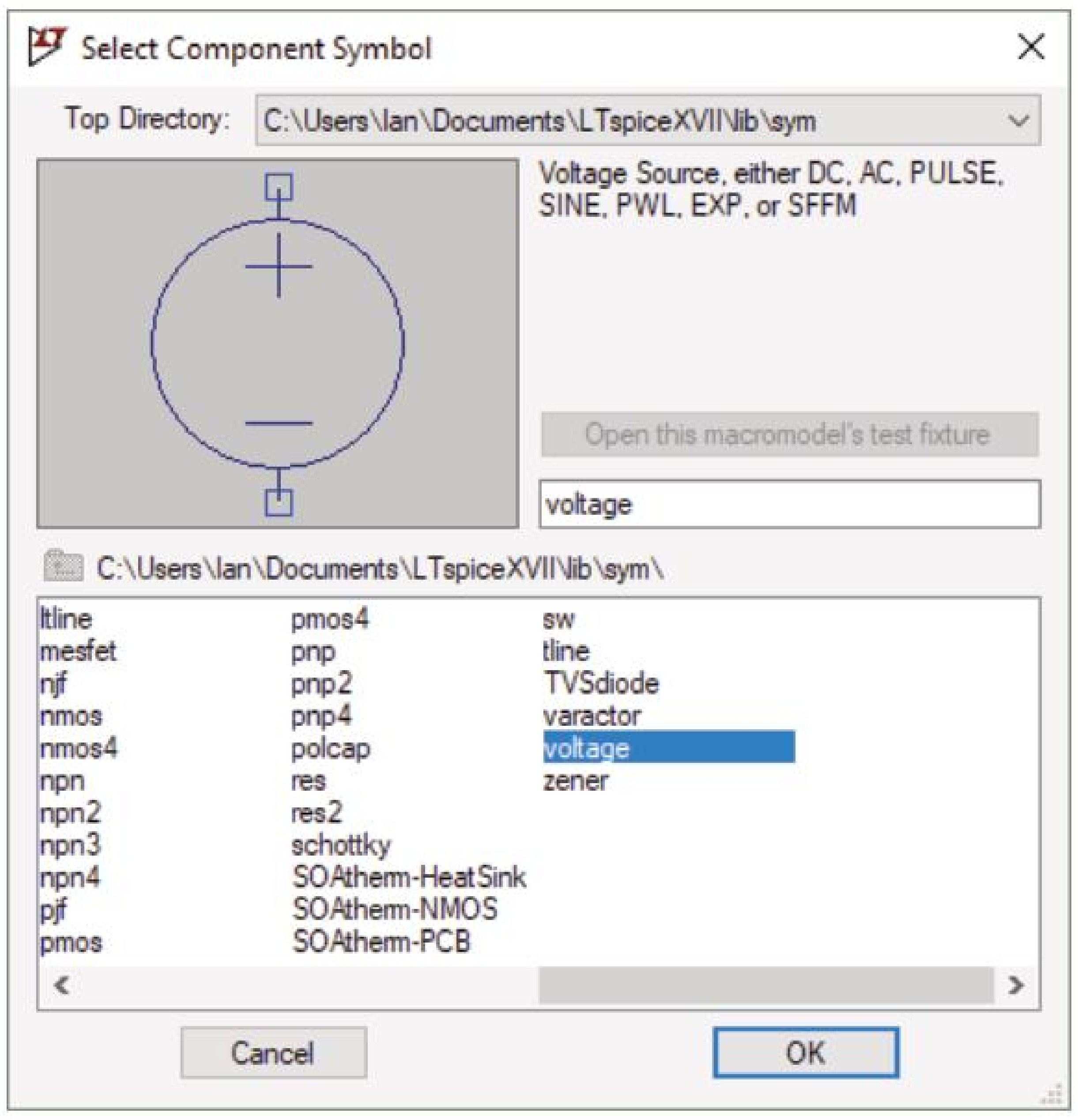
In terms of SPICE simulation, the different lab set-ups in Fig.2 and Fig.3 correspond to what are referred to as different analyses or simulation commands. The lab scenarios we have just discussed relate to SPICE transient analysis (Fig.2) and AC analysis (Fig.3). Transient analysis allows us to plot circuit waveforms against time and generally requires you to define some form of time-varying input signal. AC analysis calculates circuit signal levels over a specified range of frequencies and allows you to plot graphs such as the variation of gain and phase shift with frequency.

Installation and set-up

To install LTspice, download it from the LTspice Design Center page on the Analog Devices website: www.bit.ly/2nsvKzT. At the time of writing, the latest software is version XVII and is available for Windows 7, 8 and 10 (and XP as 'end of support') and for Mac OS X 10.7+. The installation (tried on Windows 10) is straightforward.

After finishing the software install LTspice runs some 'preparation' steps for the example/library files, which are included in the download, and then opens (see Fig.4). Sometimes when LTspice starts it will ask if you want to check for updates – this is for the libraries as well as the executable and should be done unless you are very short of time. You can also update by using Tools > Sync Release from the main menu.

The user interface presented when LTspice opens has a small main menu and a row of command buttons (you may need to resize to see them all). Most of the buttons are greyed out if a file is not open. Once a file is open, the buttons will become active and additional menu items will appear, depending on the currently selected file type (eg, schematic or graph of results). The buttons have tooltips to tell you their function, even when greyed out. It is worth spending a few moments hovering the mouse over the various buttons to find out what they do. There is a built-in help system (Help > Help topics from the menu), which is a set of pages and topics you can browse, search or access by index. The following descriptions of use apply to the Windows version. It is assumed that the Mac version is similar.


Select Component Symbol

Top Directory: C:\Users\Ian\Documents\LTspiceXVII\lib\sym

Voltage Source, either DC, AC, PULSE, SINE, PWL, EXP, or SFFM

voltage

C:\Users\Ian\Documents\LTspiceXVII\lib\sym\

Fig.5. Add component window with voltage source selected.

Simulation

To simulate a circuit we have to first draw a schematic (or open an existing one). To start a new schematic, click the New Schematic button or use the File > New Schematic command from the menu. Our schematic requires a capacitor and a resistor and these are available to add to the schematic directly from buttons, along with inductors and diodes. Other components require the use of the component button.

Start by clicking on the capacitor button and move the mouse over the blank schematic. Click on the background to place the capacitor. It is automatically labelled 'C1', but you can change this later if you want. The editor is immediately ready to add another capacitor. LTspice editing commands remain active until you select a new command or press the escape key (Esc). Press escape and/or click the resistor button, but do not immediately click to add the resistor to the schematic. Note that it is not oriented in the same direction as in Fig.1. You can use the rotate and mirror buttons, or the Ctrl-R and Ctrl-E hot keys to reorient components prior to placing them. Change the resistor orientation and place it as in Fig.1.

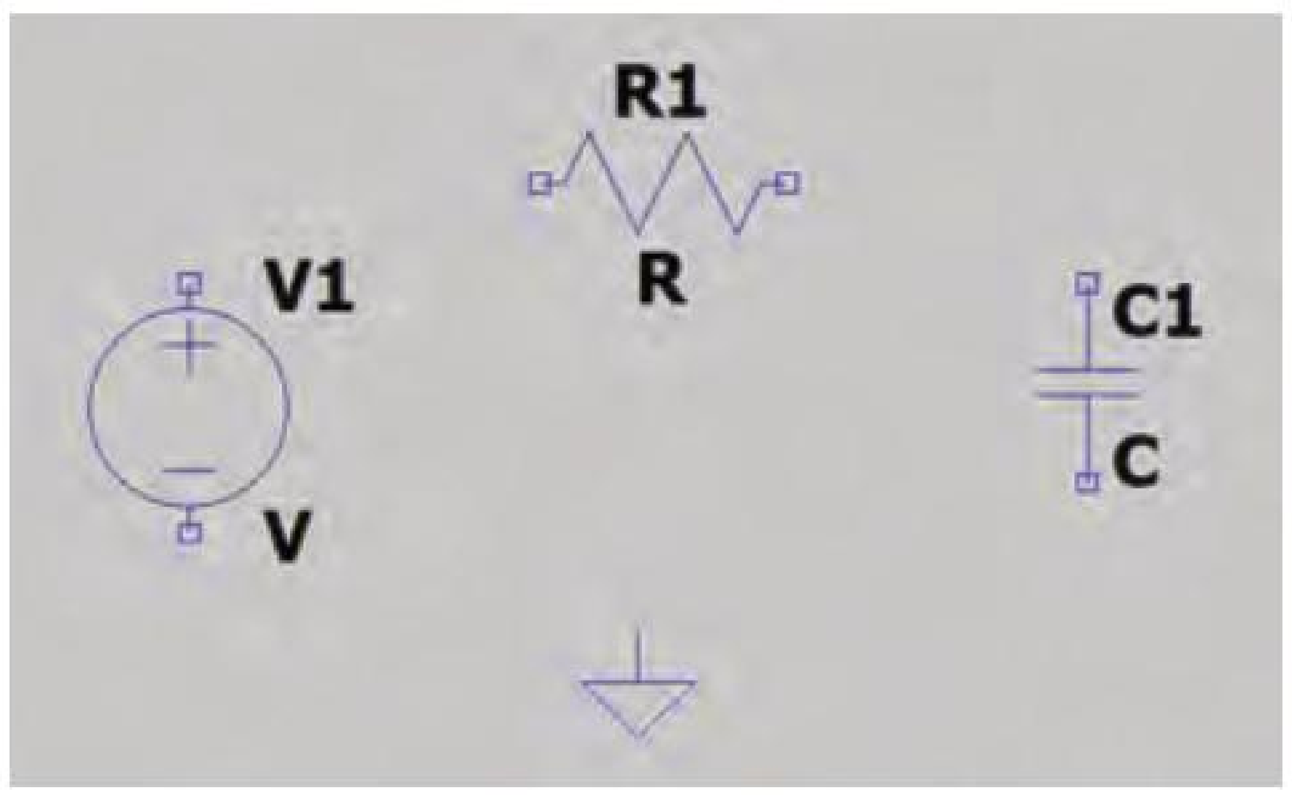
When editing a schematic you can zoom using the mouse scroll wheel. If you get lost you can get a sensible view of your schematic using View > Zoom to fit. If you place unwanted components hit the delete key or use Edit > Delete. The cursor shape changes to indicate the active command. With commands such as delete you can click individual components or click and drag to marquee select multiple components in an area. Remember, escape cancels the command.

Ground, voltage sources and wiring 'nets'

All SPICE circuits must have a ground connection, if it is not included then the simulation will fail, although LTspice will simply tell you if you forget and try to run a simulation without one. Ground has its own button (or use Edit > Place GND). Place a ground on your schematic and hit escape. In order to perform a simulation we usually need to include some form of signal source – the equivalent of a lab signal generator, or even the battery-switch combo mentioned in our earlier discussion. There is no button to directly do this, so click the Component button (or Edit > Component). In the window that opens, scroll to the right and select the 'voltage' item, as shown in Fig.5. Note the wide range of components listed and the fact that a description and symbol is displayed when you select one. Click OK and add one voltage source to the schematic, which should now be similar to Fig.6.

The next step is to wire up the schematic. Click on the Add Wire button (or used Edit > Add Wire) and then click on one of the square terminal points for the components.

Fig.6. Components placed on the schematic.



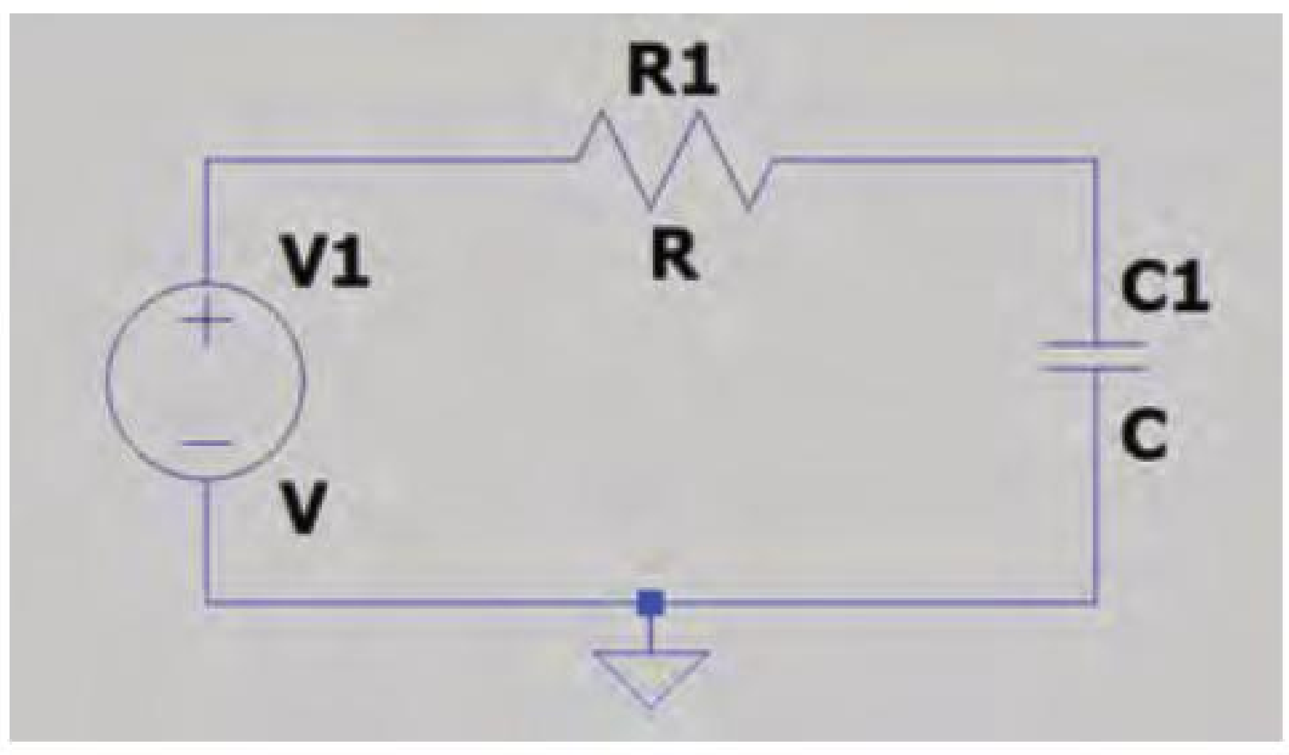
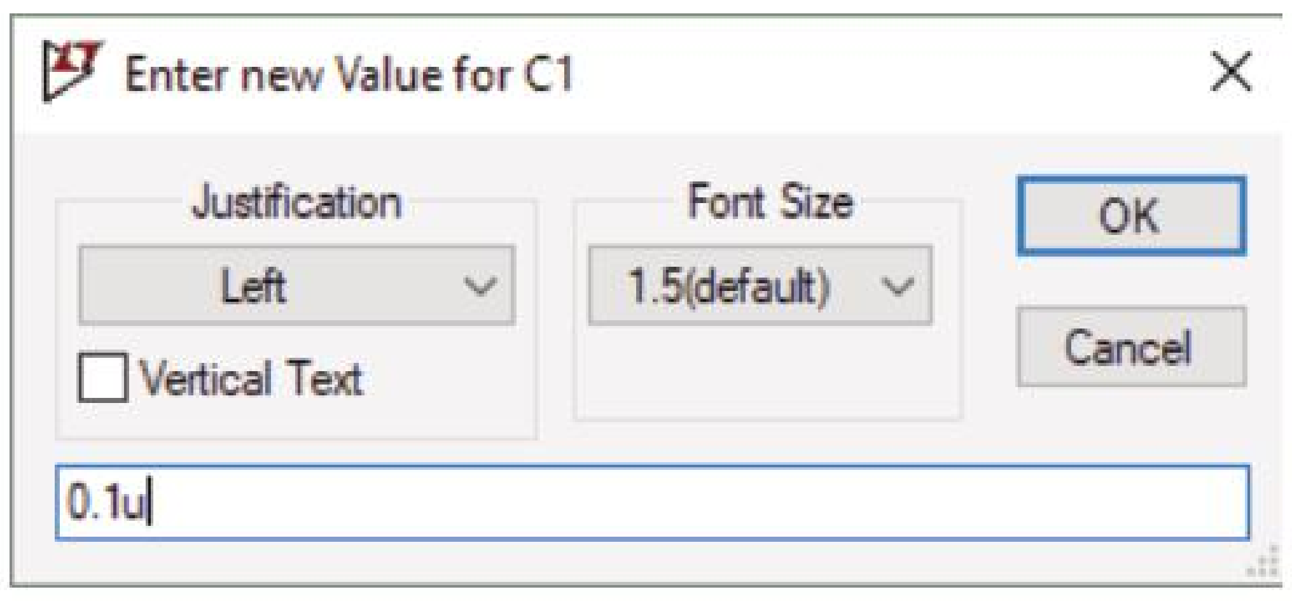


Fig.7. Schematic with wiring added.

Click on the background to start a new wire segment at 90 degrees to the current section and on another component terminal to complete the wire. Click right to cancel the current segment if required. Hold down the control key to draw lines at other angles, and hit escape to cancel the Add Wire command. Clicking on an existing wire as you draw a new one will create a join. Now complete the wiring, which should look similar to Fig.7.

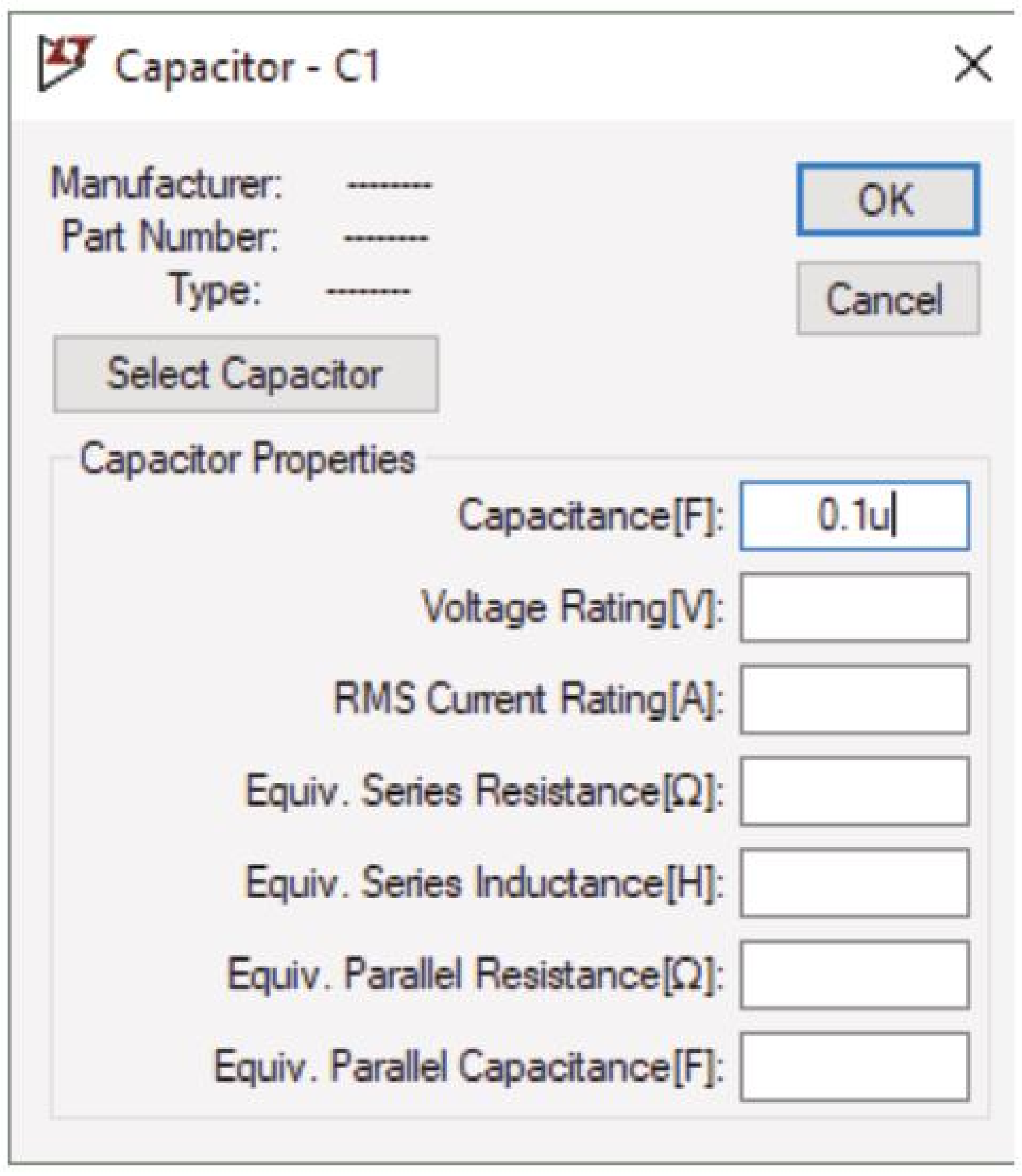
The next step is to enter component values and edit their names if required. Right click directly on the C character (which is currently the value of C1) to open a window, which allows the value to be entered (see Fig.9). Type in **0.1u** and click OK. If you right-click the centre of the capacitor symbol you get the opportunity to enter more detailed information (see Fig.10), you can also select specific commercial devices (via Select Capacitor) if they are in the library, which will set all the parameter values defined for that device. These include examples of the parasitics, which we discussed earlier. Right-clicking on the 'C1' text allows us to rename the capacitor, but this is unnecessary here. Enter **1.0k** as the value of R1 and click OK.



☐ Vertical Text

0.1u

Fig.8. Enter component value.



Manufacturer: --------
Part Number: --------
Type: --------
Capacitance[F]: 0.1u
Voltage Rating[V]:
RMS Current Rating[A]:
Equiv. Series Resistance[Ω]:
Equiv. Series Inductance[H]:
Equiv. Parallel Resistance[Ω]:
Equiv. Parallel Capacitance[F]:

Fig.9. Enter detailed component parameters.

Unit suffixes

Note the use of engineering unit multipliers (k and u) in the component values. A full list is given in table 1. These are *not* case sensitive and so are *not* completely standard. A common mistake is to type `1M` for a one-megohm (1.0MΩ) resistor – in LTspice `1M` is interpreted as meaning a one milliohm resistor (1.0mΩ = 0.001Ω). You need to type `1Meg` for a 1.0MΩ resistor. Scientific notation can also be used (eg, 1.0e3 and 1.0e-7). Fuller details of text formats can be found on the General Structure and Conventions page of the help.

Table 1: unit multipliers in SPICE

Suffix	Name	Multiplier
T	tera	10^{12}
G	giga	10^{9}
Meg	mega	10^{6}
K	kilo	10^{3}
M	milli	10^{-3}
u or µ	micro	10^{-6}
n	nano	10^{-9}
p	pico	10^{-12}
f	femto	10^{-15}

LTspice automatically names every wire in the circuit (complete wires are referred to as 'nets' in SPICE). You can see the net names in the status bar (bottom left) if you hover over the wire on the schematic. The automatic net names are N001, N002…, so it is usually best to enter your own meaningful names for any net where you want to look at data. To do so, click the Label Net button (or use Edit > Label Net). In the window enter the required name, click OK and place the small square under the text directly over the wire you want to name and click. Label the input **in** and output **out**. The schematic should now look like Fig.10.

Set up the voltage source

The final schematic editing stage is to set up the voltage source. What we do here depends on the analysis we want to run. For this example we will start with a transient simulation using pulse inputs. With reference to the theory, and the component values used, the time constant *RC* is 100µs, so in the absence of any specific input requirements, the pulse should probably be at least four or five times this duration. This will allow the capacitor to reach nearly full charge. Therefore 500µs (0.5ms) seems like a convenient figure, giving a period of 1ms for a combined charge and discharge cycle. If we apply a small number of cycles of a 1ms-period square wave we should be able to see the RC charge/discharge curves clearly.

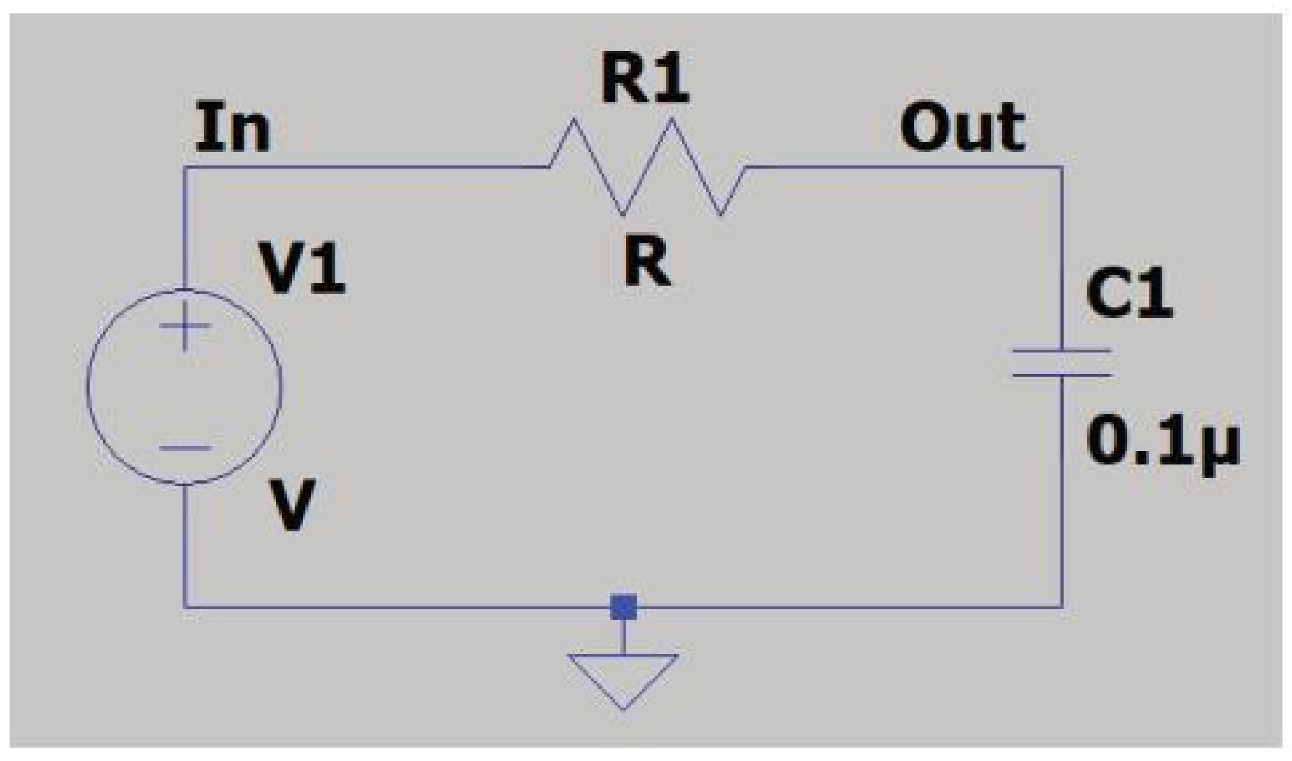
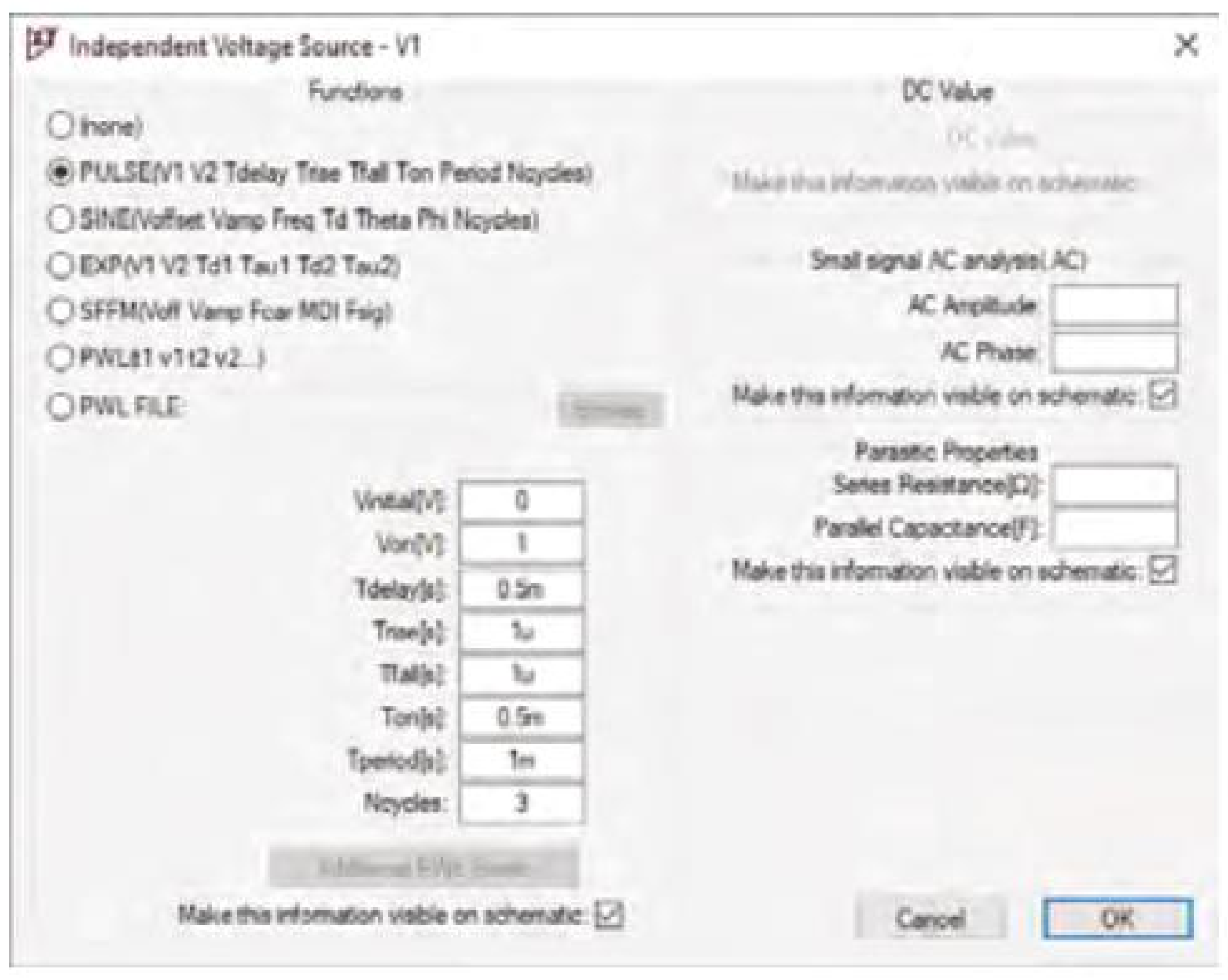


Fig.10. Schematic with component values and net names added.


Independent Voltage Source - V1
Functions
DC Value
Small signal AC analysis(.AC)
Parasitic Properties
Cancel
OK

○ (none)
● PULSE(V1 V2 Tdelay Trise Tfall Ton Period Ncycles)
○ SINE(Voffset Vamp Freq Td Theta Phi Ncycles)
○ EXP(V1 V2 Td1 Tau1 Td2 Tau2)
○ SFFM(Voff Vamp Fcar MDI Fsig)
○ PWL(t1 v1 t2 v2...)
○ PWL FILE:

Vinitial[V]: 0
Von[V]: 1
Tdelay[s]: 0.5m
Trise[s]: 1u
Tfall[s]: 1u
Ton[s]: 0.5m
Tperiod[s]: 1m
Ncycles: 3
Make this information visible on schematic: ☑

AC Amplitude:
AC Phase:
Make this information visible on schematic: ☑
Series Resistance[Ω]:
Parallel Capacitance[F]:
Make this information visible on schematic: ☑

Fig.11. Setting up the V1 voltage source to produce pulses.

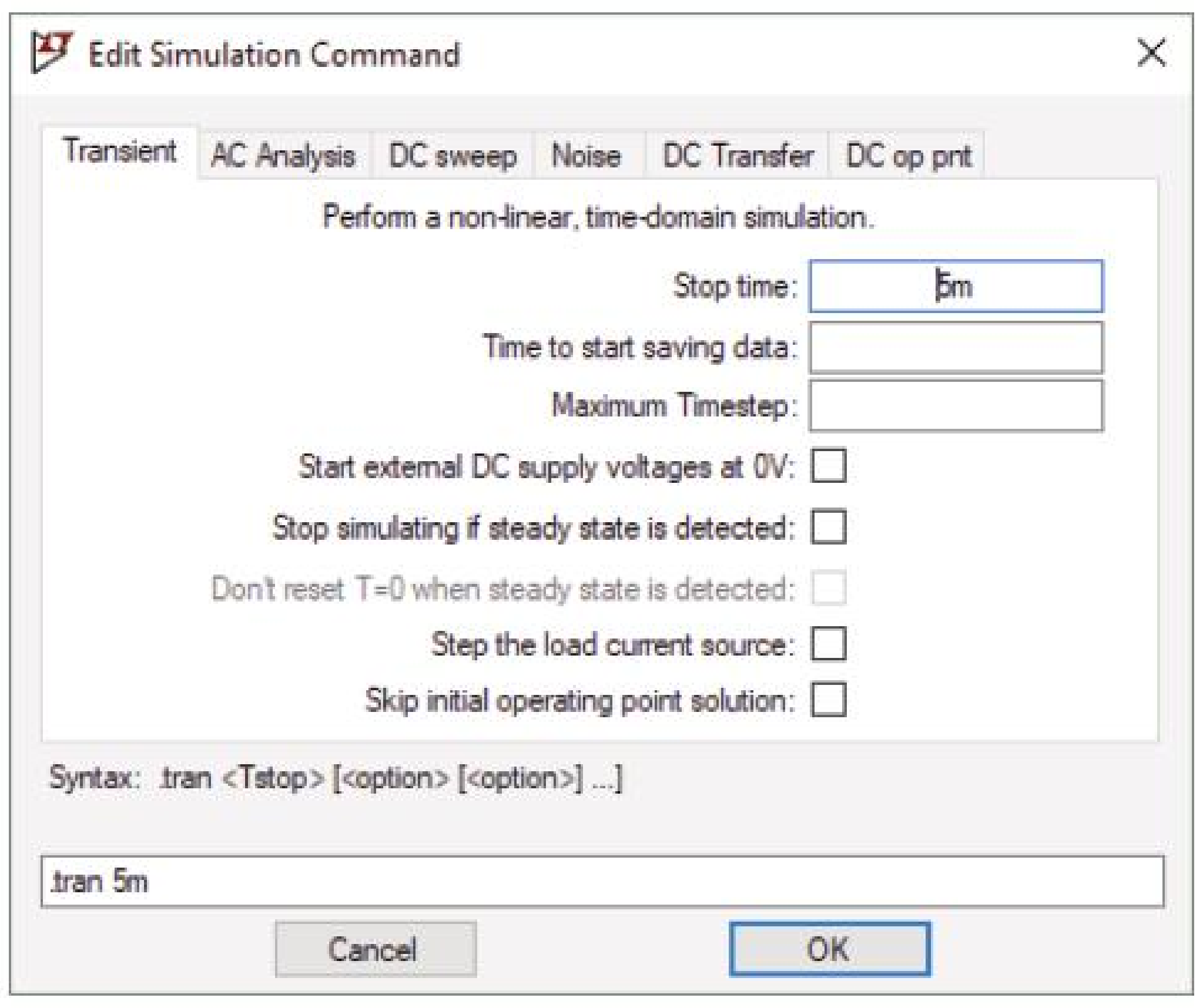
If we right-click on the V next to the voltage source we can set a value, but we do not get full access to the set-up window, so right click in the middle of the voltage source symbol, and then click the Advanced button. This allows us to set up a variety of possible waveforms (see Fig.11). Select PULSE from the Functions list and enter the details:

```
Vinitial = 0
Vob = 1
Tdelay = 0.5m
Trise = 1u
Tfall = 1u
Ton = 0.5m
Tperiod = 1m
Ncycles = 3
```

This will cause the V1 voltage source to produce three cycles of a pulse waveform in which each cycle is 1ms long, with the pulse on for 0.5ms (half the 1ms period – so the square wave is symmetrical). The voltage will switch between 0V and 1V in 1µs (the pulse rise and fall times). After entering the wave function data, click OK.

Running our first simulation

Before running a simulation we have to set up the simulation command. Do Simulate > Edit Simulation Command from the menu. In the window that opens (see Fig.12) the tabs represent the various analysis types. Select the Transient tab, enter **5m** as the stop time (for a simulation duration of 5ms) and click OK. Then click on the schematic to place the text of the simulation command SPICE directive (**.tran 5m**) somewhere convenient. This text must be placed on the schematic for it to be possible to run the simulation. The schematic should now be similar to Fig.13. The schematic is now complete and should be saved. It is advisable to create a new folder for each circuit simulated in LTspice and locate this somewhere away from the install and library folders.


Edit Simulation Command
Transient
AC Analysis
DC sweep
Noise
DC Transfer
DC op pnt
Cancel
OK

Perform a non-linear, time-domain simulation.

Stop time: 5m
Time to start saving data:
Maximum Timestep:
Start external DC supply voltages at 0V: ☐
Stop simulating if steady state is detected: ☐
Don't reset T=0 when steady state is detected: ☐
Step the load current source: ☐
Skip initial operating point solution: ☐

Syntax: .tran <Tstop> [<option> [<option>] ...]

.tran 5m

Fig.12. Setting up the simulation command.

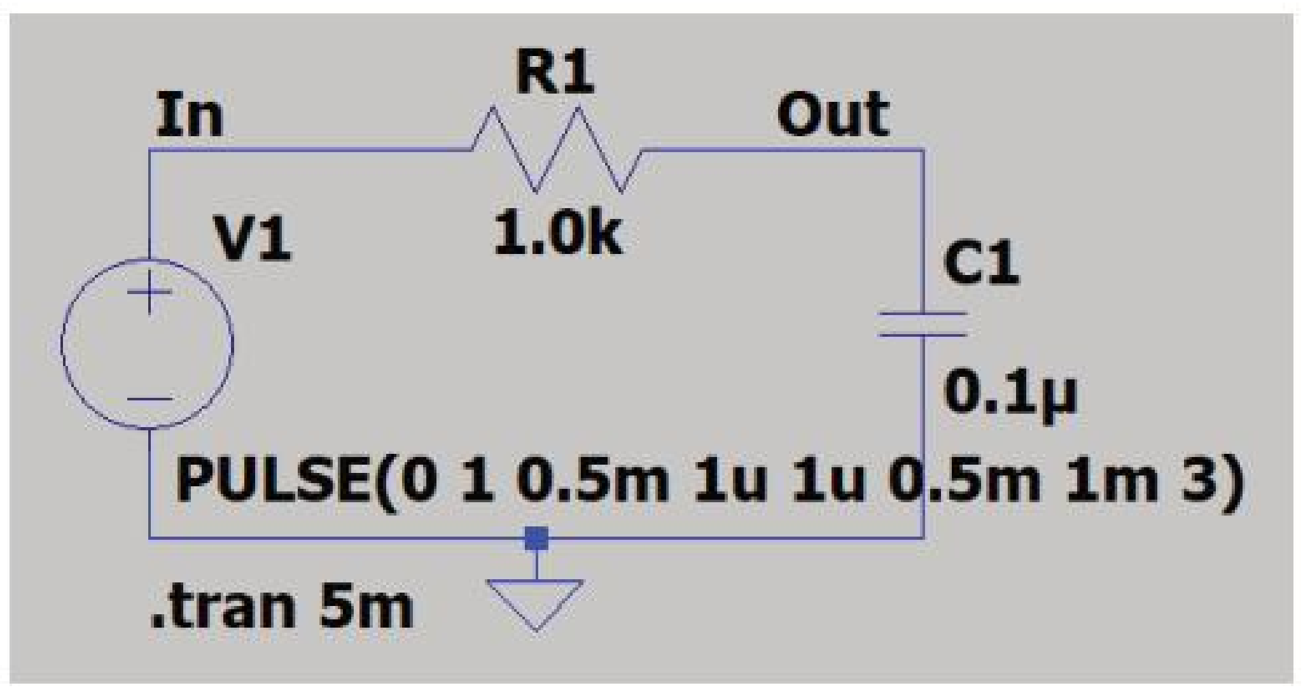

In
R1
Out
V1
1.0k
C1
0.1µ
PULSE(0 1 0.5m 1u 1u 0.5m 1m 3)
.tran 5m

Fig.13. Schematic with source setup and simulation command SPICE directive.

We are now ready to run the simulation. Simply click on the Run button or do Simulate > Run from the menu. All being well, a blank graph/waveform window will open. To display the input waveform right click in the black background of the graph area and select Add Trace. Select V(in) from the list that appears and click OK.

Repeat the process, selecting V(out) this time. The result should be a graph of the input and output waveforms, as shown in Fig.15. This completes our first simulation.

Next month, we will look in more detail at displaying and investigating results and look at other analysis types.

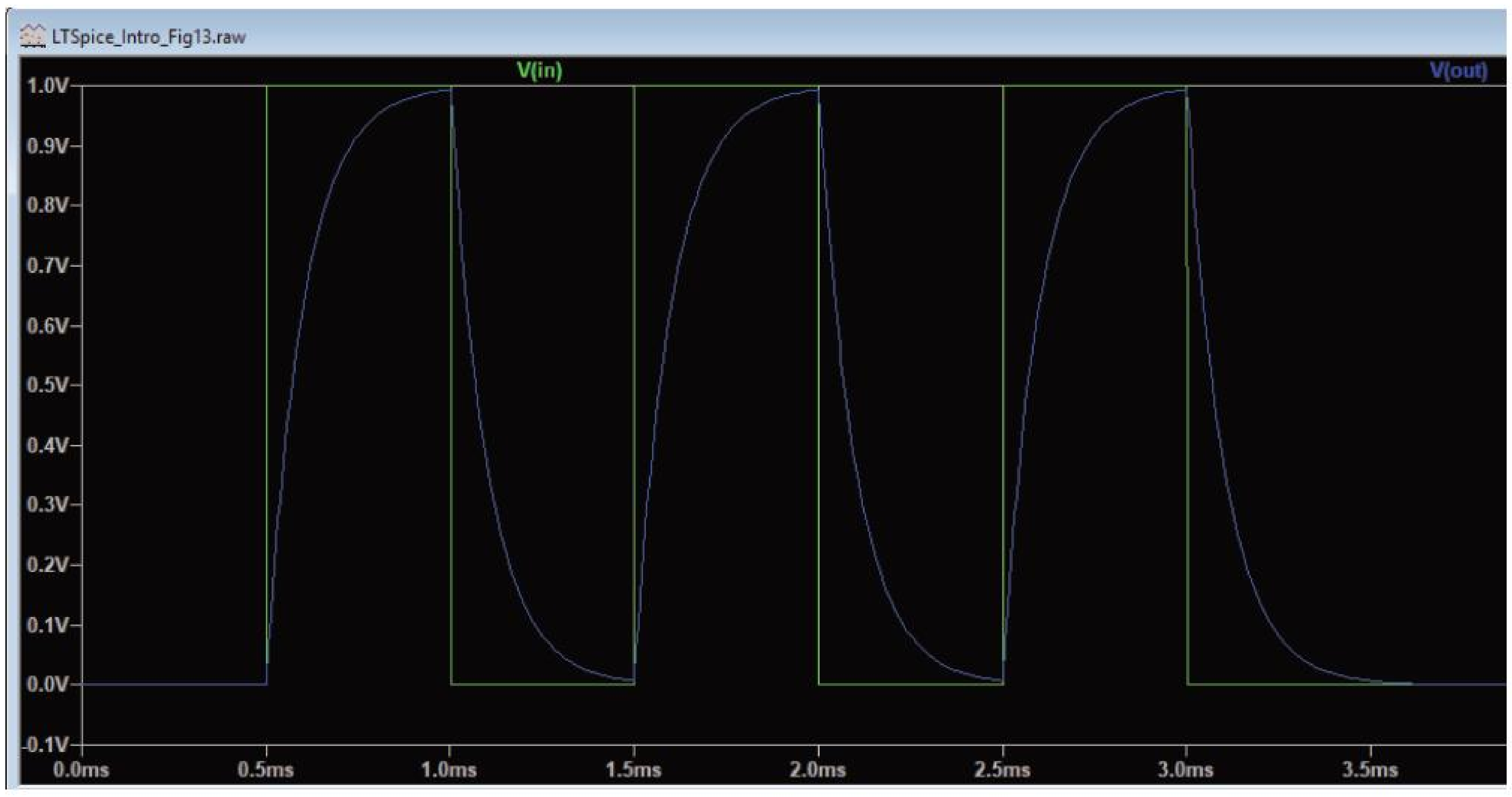


Fig.14. Transient simulation results for the circuit in Fig.13.

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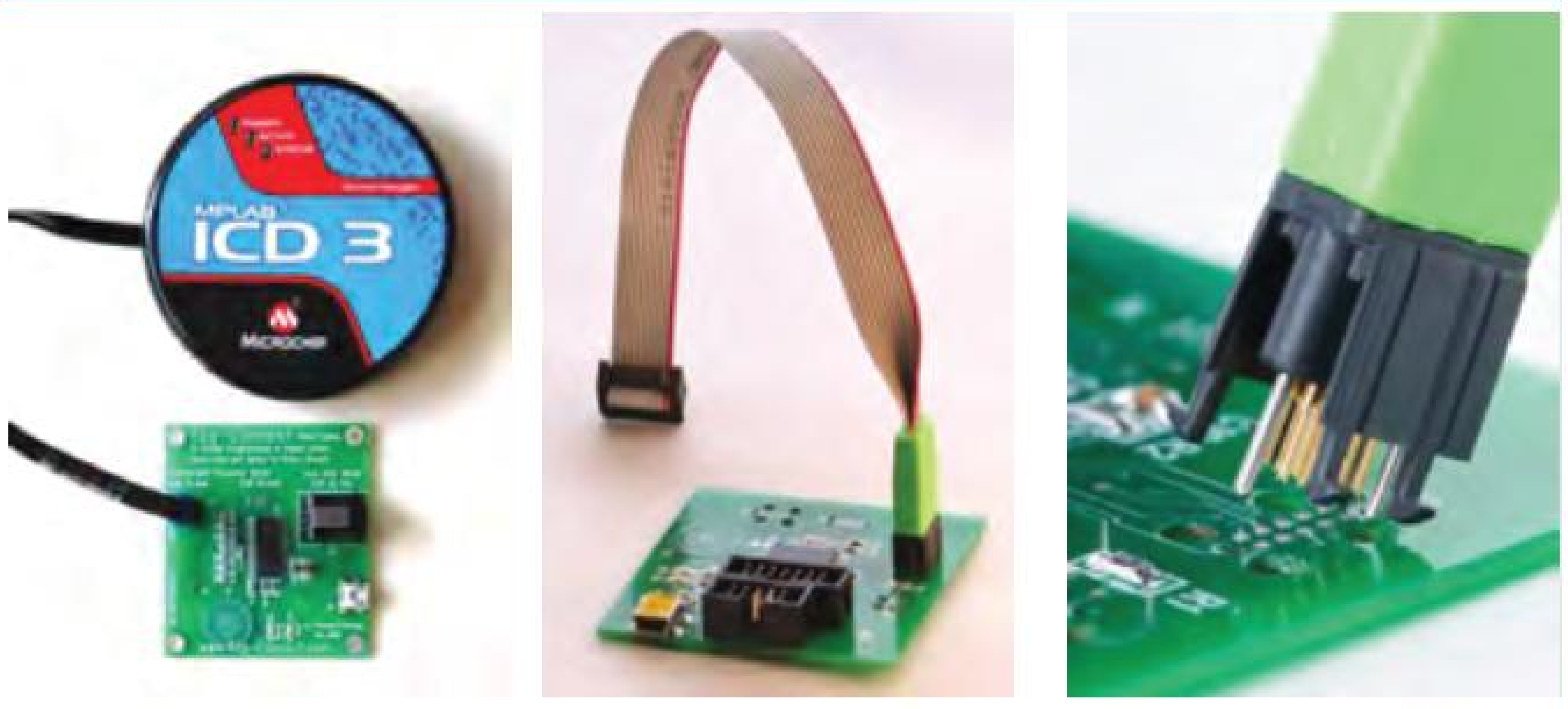

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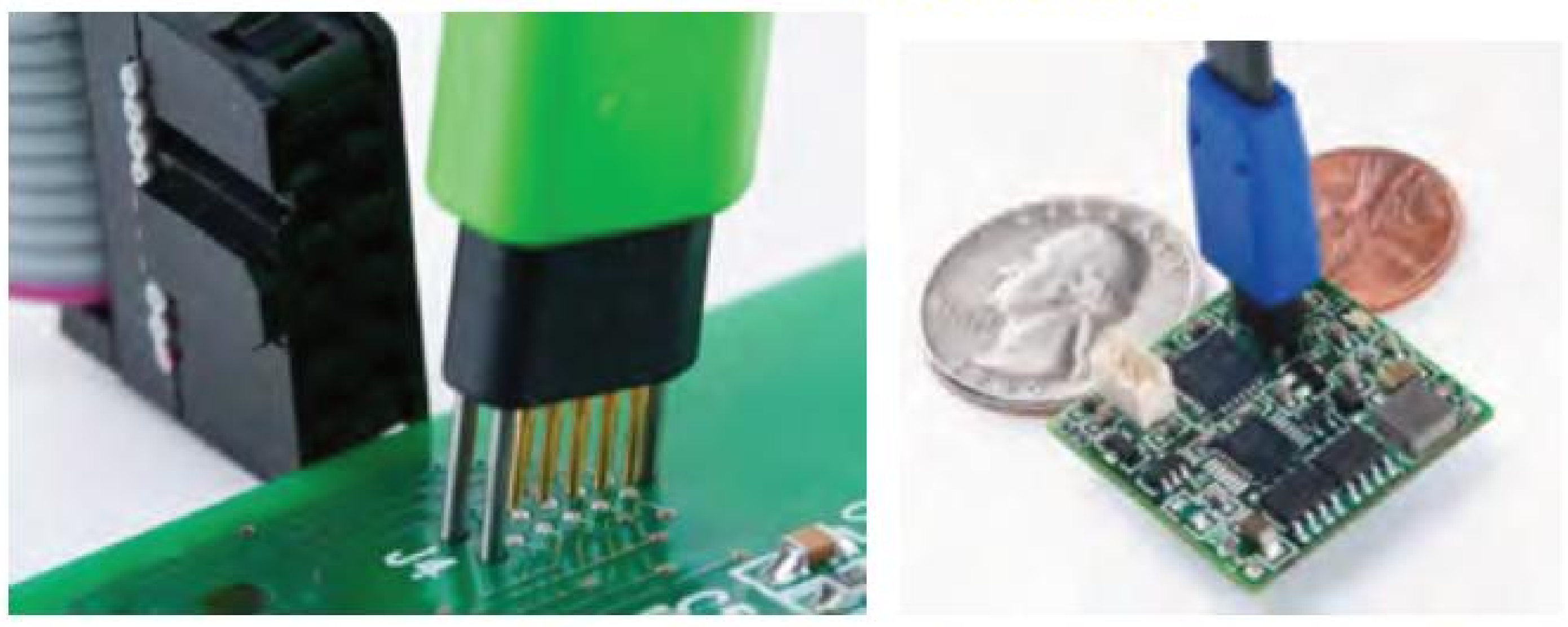

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NET WORK

by Alan Winstanley

EEWeb forum update

As regular readers are aware, last year we took the difficult decision to close our legacy discussion forum – the *EPE Chat Zone* (**www.chatzones.co.uk**). However, the original posts dating back to 2005 will be available for the foreseeable future, or until server upgrades render it no longer possible to continue. If you are tussling with a legacy *EPE* project, it is worth searching the old *EPE Chat Zone* for any updates or contemporary advice from fellow readers.

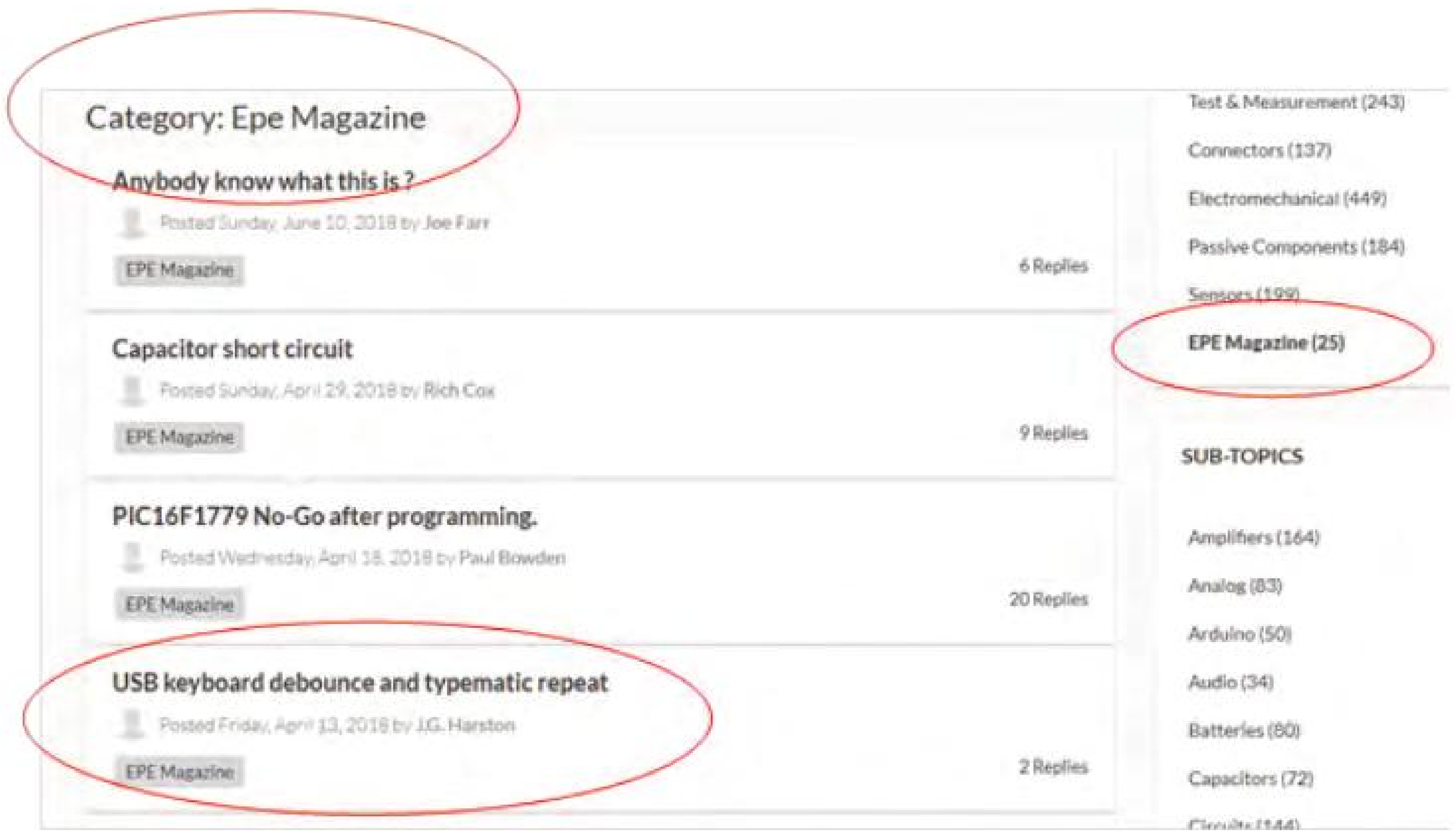
Fortunately, that was not the end of *EPE* reader online discussion, support and knowledge sharing – the electronics design website EEWeb generously offered us a corner in their own forum, and readers have started to make themselves at home. EEWeb is owned by media firm Aspencore, whose brands include *EE Times*, Datasheets.com, Schematics.com, *EDN* and elektroda.pl, as well as other well-known electronics sites. This means that neither *EPE* nor Wimborne Publishing own the forum, and so we cannot moderate any of the messages posted there by *EPE* subscribers or other visitors.

This month, we have good news for readers; EEWeb has kindly enhanced our *EPE* presence and converted it into a top-level group in its own right. It is also now possible to attach images and files to forum posts. The older EEWeb posts have been migrated to the new *EPE Magazine* category and the direct URL is: **www.eeweb.com/forum/category/epe-magazine**

You'll also find surrounding content and tools on the EEWeb that will appeal to electronics professionals and hobbyists alike, so do be sure to register at EEWeb and see what's on offer.

Say 'Ahhh...'

Sitting with one's mouth wide open in a dentist's chair is not the best way to hold a conversation, but both my dentist and I agreed that smartphones have a lot to answer for. Of course, they bring enormous benefits that go way beyond making phone calls. My plumber uses one with a spirit level app when installing pipework, and I can capture photos of domestic wiring before taking everything apart. I can also use GPS and satnav, or fire up Whatsapp to blip some photographs to friends, and so on.



Category: Epe Magazine

Anybody know what this is ?
Posted Sunday, June 10, 2018 by Joe Farr
EPE Magazine
6 Replies

Capacitor short circuit
Posted Sunday, April 29, 2018 by Rich Cox
EPE Magazine
9 Replies

PIC16F1779 No-Go after programming.
Posted Wednesday, April 18, 2018 by Paul Bowden
EPE Magazine
20 Replies

USB keyboard debounce and typematic repeat
Posted Friday, April 13, 2018 by J.G. Harston
EPE Magazine
2 Replies

Test & Measurement (243)
Connectors (137)
Electromechanical (449)
Passive Components (184)
Sensors (199)
EPE Magazine (25)

SUB-TOPICS

Amplifiers (164)
Analog (83)
Arduino (50)
Audio (34)
Batteries (80)
Capacitors (72)

EPE's online forum at EEWeb.com has had an upgrade

On the other hand, we agreed that our always-on smartphone culture had skewed the values of society and civility. They have created a sense of immediacy, entitlement and effortless access to everything that the online world puts our way, while at the same time bombarding users with screens full of news, fake news, drama and social media banter. (Why social media users conduct their business 'in public' on, say, Facebook, with scant regard for their own privacy is something that still puzzles me.) We've reached the point where a smartphone (or tablet) can deliver the unrestricted power of communications to a new generation of undiscerning, wide-eyed users who have never known life without the Internet.

Missing from the Internet's evolution has been a lot of grey hair and wisdom, as bright and enthusiastic early adopters climbed aboard the rollercoaster revolution of the web. The respected business management guru Dr Ichak Adizes drew his now famous graph depicting the lifecycle of a typical businesses – starting with 'Infant', 'Adolescence', 'Go-go' then 'Prime', after which ageing sets in until the business eventually withers and dies. You can read more at the Adizes Institute: **https://tinyurl.com/yaykzxga**

History is littered with success as well as some spectacular failures. The UK fashion upstart Boo.com was one example of a young web firm crashing and burning due to 'infant mortality'. Other names such as MySpace and Friends Reunited only ever reached 'Adolescence', while other brands continue their upwards trajectory, reaching 'Prime' and dominating the market.

In 2004, a CNBC news anchor interviewed an earnest young Mark Zuckerberg, who ran a start-up social media site for US universities called 'The Facebook'. He initially thought maybe 400-500 users might sign up, but by the time of the interview numbers had jumped to 100,000 –'who knows where we're going next?', he added (2.3 billion by 2018 would be the answer). After signing up maybe 100-200 universities he wanted to launch a 'bunch of site applications' that would keep people coming back to the site and maybe make 'something cool'. 'The Facebook' was originally dedicated to students eager to share their profiles, contact details, phone numbers, academic record and more besides. Visitors could then browse around peoples' friends and their online identities and find 'interesting information about people' as he put it – in other words, nosey around the profiles of people desperate to be heard. You can see the CNBC footage at: **https://youtu.be/cUNX3azkZyk**

Facebook caught the tide of social media and the rest is recent history. However, at the end of July Facebook's stock suffered the largest one-day fall in corporate history, with 19% wiped off its value: earnings had been hit by the knock-on effects of a spate of fake news scandals, spam, clickbait, accusations of malign influence on election campaigning and a plethora of security and privacy failings. The levelling off of Facebook user numbers, its need to invest in new AI systems to screen out fake news, and the extra resources announced to combat fake accounts, spam and dishonest advertising have hit the share price, but investors are assured that a chastened Facebook is in for the long haul.

A young Mark Zuckerberg interviewed on CNBC in 2004 revealed his new social media platform, 'The Facebook', had reached 100,000 subscribers.

Facebook had been forced to smarten up its act after its chickens came home to roost. In the UK, Facebook is running reassuring but infantile TV adverts saying how fake news is 'not OK' and how Facebook is changing for the better.

A digital decade

Has the Internet as a whole peaked at 'Prime'? Britain's communications watchdog Ofcom recently published a survey about the habits of Britain's Internet-enabled culture. The survey – *A Decade of Digital Dependency* – throws into sharp relief the way in which UK society has been influenced, sometimes adversely, by the explosive growth of Internet usage. Interestingly, 78% of people now have a smartphone (95% of 16-24 year olds) and for the first time women now spend more time online than men. Desktop PC ownership has tumbled 41% in a decade in favour of tablets and smartphones, but only 13% own a smart speaker like Google Home or Amazon Echo. Throughout the day, users check their phones every 12 minutes on average, says Ofcom. This affliction can be attributed to 'FOMO' – the 'fear of missing out'. According to behavioural economic theory, humans often hate the idea of losing out on something a lot more than they like the idea of gaining something instead. Marketers exploit FOMO to great effect when trying to sell a product or service. We check our phones just in case something new is happening that we wouldn't want to miss.

Some 43% of people admit they spend too long online, but a third would feel isolated without Internet access. A sample YouTube vox pop put together by Ofcom offers a glimmer of hope, as a number of interviewees suggested they were tired of being online and could possibly live without a smartphone, or they had relegated it from having pole position in their lives. Conversely, some younger people admitted they live out their entire lives online, which is something we should all worry about. How things have changed since the 1990s: *Net Work* readers might enjoy this cringeworthy YouTube video, *The Kid's Guide To The Internet* at: **https://youtu.be/mfMrVKnGzwg**

What goes around comes around, and there's a possibility that in years to come, many smartphone users will grow tired of logging in, checking out, tagging, emoting, messaging, 'buying it now' and all the encumbrances that smartphones bring them, and society might actually learn to socialise and interact more normally once again. *A Decade of Digital Dependency* is at: **https://tinyurl.com/ycuxo3as** and its YouTube video is at **https://youtu.be/SaKCEb8qgNI**

Scrolling news

Another Ofcom report, entitled *Scrolling news: The changing face of online news consumption*, makes for fascinating but troubling reading. It highlights a multitude of trends and effects on the way the new always-on smartphone generation is dealing with and processing so-called 'news'. A small sample audience kept detailed records of their news consumption – recording what they saw and where they saw it, covering both digital and print platforms. The sample set was then intensively interviewed to determine how they *saw themselves* handling news, compared with what they *actually* did based on screen shots and their browser histories.

Almost all of them obtained their 'news' online using a smartphone and not in print or on a PC. Survey respondents felt bombarded by the constant supply of online news, but they also felt compelled to keep constantly up to date, sometimes to make it appear that they were well-informed about current affairs. The report noted how small-screen UI design was inherently biased towards the 'passive' consumption of news and did not lend itself to exploring, verifying, cross-checking or researching: unlike a desktop, there isn't enough screen real-estate on a smartphone screen to do that.

Encouragingly, some astute and savvy smartphone users did try to verify what was presented to them, even though some would clearly lack the skills or experience to do that very effectively. It seemed that while many might instinctively feel when something was not quite right, it was easier to carry on blindingly consuming news regardless of its accuracy. There were many factors that controlled how the sample audience dealt with 'news', and choosing quantity over quality was one of them. The report confirmed how the sample majority had only a superficial grasp of any 'news' they consumed, and they processed the news 'at a very shallow level... struggling to recall key facts a day or two later.' Some who tried to kick the 'FOMO' habit would succumb again, fearing that they were missing out on something!

The report showed that many users failed to recognise how much time they spent on their personal newsfeed. Users tended to deceive themselves and one interviewee claimed she 'would probably have stopped scrolling a while ago' after checking Facebook's newsfeed for ten minutes, despite data proving she would spend an hour every morning passively consuming news. Highlighting the need to be more discerning and not passive about 'news' made some realise that they weren't really interested in the news anyway.

More worrying was the claim that online media aggregators like Facebook and Google had 'blurred' the news, with many smartphone users choosing simplicity and ease of use over quality and accuracy. They got their 'news' from social media, not traditional journalistic sources like Sky News or the BBC, for instance. Ofcom's report and its conclusions are fascinating reading and can be downloaded from: **http://bit.ly/2vCyajf**

Testing the veracity of online news was the main objective of the EU-funded Pheme Project (www.pheme.eu). Pheme was the Greek goddess of fame and a habitual rumourmonger and gossip. The Pheme Project aimed to develop algorithms that could identify fake news and rumours. The same so-called fake news has been branded by the UK's Culture, Media and Sport Select Committee as a danger to our democracy, according to its recent *Disinformation and 'fake news': Interim Report* at: **https://tinyurl.com/ycx9kejy**. This also embraced the recent Facebook crises and the threats of Russian interference in political campaigns. It also examines the grossly distorting effect that social media has on a user's 'digital literacy' – people's ability to discern news and understand where it really came from and whether it can really be trusted.

The report calls for an educational levy to be raised by social media organisations to fund improvements in digital literacy, which the government now rightly places alongside the core skills of reading, writing and arithmetic. In August, Facebook USA opened its own 'Digital Literary Library' offering teaching tools to help youngsters become more aware when they access 'news' content. This is what unbridled online news consumption has come to.

See you next month for more *Net Work*. You can contact the author at: **alan@epemag.net**

AUDIO OUT

By Jake Rothman

Analogue synthesis – Part 3

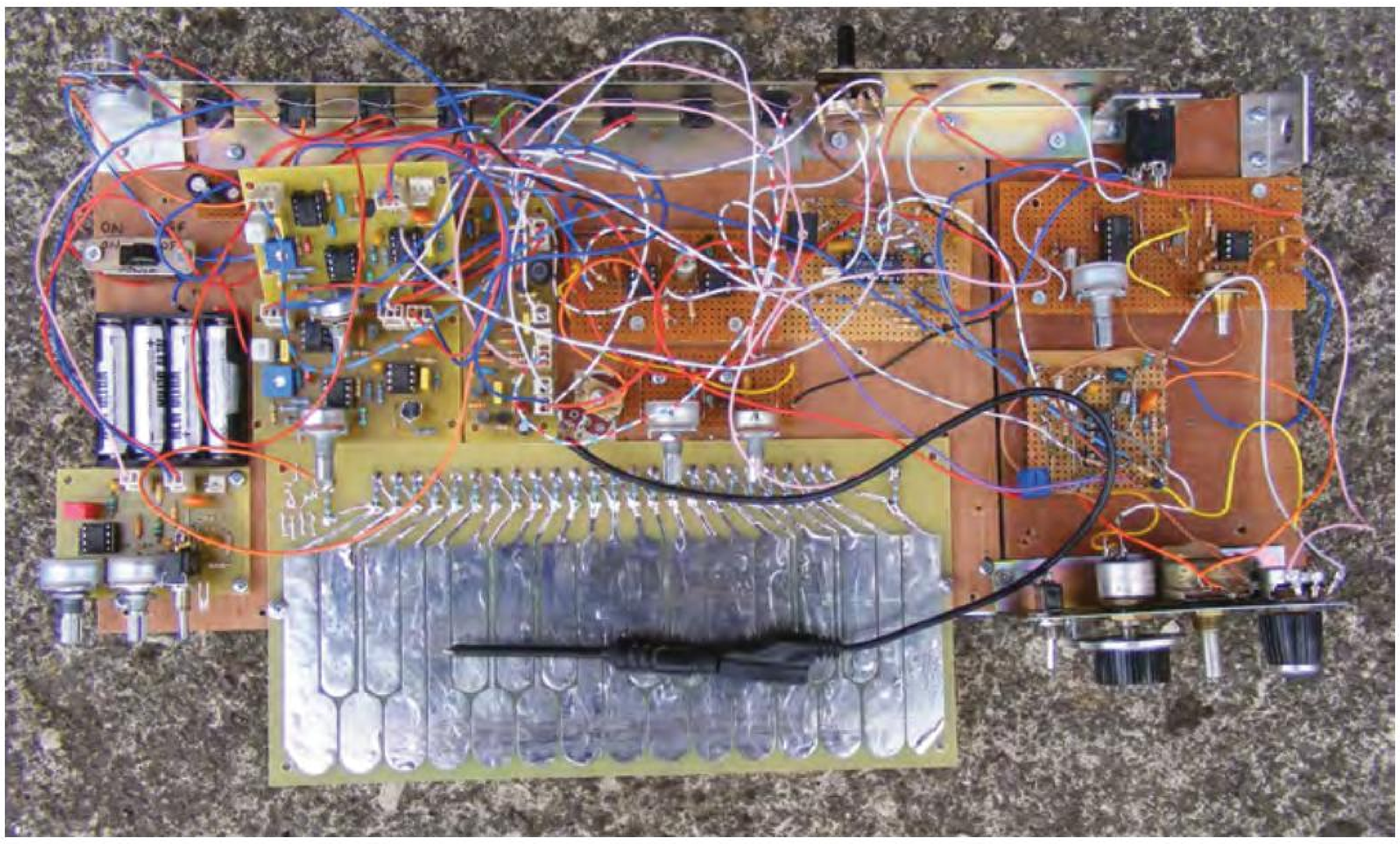


Fig.54. It looks a mess, but sounds wonderful; just like a Mini Moog, but with components costing one hundredth the price.

In *Part 2* last month, I covered some basic building blocks of an analogue synthesiser and built a few Veroboard modules. This month, we're going to build the keyboard, keyboard controller and VCO (voltage-controlled oscillator) on PCBs (the voltage-controlled filter mentioned at the end of *Part 2* will be covered next month). Once committed to a PCB the circuit becomes fixed, so I've added a few improvements and corrected some errors. Analogue circuit design is never finished, just abandoned at an acceptable level of optimisation! The PCBs are all individual modules, so the system design remains flexible. When it goes into production, the modules needed will be consolidated into one PCB and the system design fixed. The system in its current state, as I write, is shown in Fig.54.

No sweat

My long-suffering students have to build my circuits, and I'm often chastened by the ambiguities they pick up. Also, musicians have occasionally destroyed my carefully crafted engineering in minutes – here are two real anecdotes. I was involved with a company building a guitar synthesiser project in the late 1980s. It used cermet (ceramic/metal) frets as potentiometric contacts with the strings, allowing slides on the notes. I didn't realise that under hot stage lights the fingers of performing guitarists got wet with sweat. That, and the amount of physical pressure they applied resulted in total disaster. Soon, all the frets were bust... and so were we. I left the company with a few Weller soldering irons and a handful of Curtis chips – a complete analogue synthesiser in one piece of silicon.

I have a long association with Colorsound guitar pedals, and discovered the hard way that Dr-Martin-shod guitarists will quickly snap off any control knob on a plastic potentiometer shaft (Fig.55) – we quickly decided to change from Omeg to Alpha potentiometers. The moral? Get real users to do the testing, not other electronic engineers, who are just too nice to equipment.

So, with the above in mind, the keyboard design here has been tested with 'sweaty fingers'! The triggering was fine, with just a hint of pitch bend. The keyboard pattern shown in Fig.56 was designed using Clip Studio Paint (PCB CAD programs don't work very well where artistic content is needed).

AMPLIFIER
INSTRUMENT
TONE-BENDER
SOLA SOUND
LONDON ENGLAND
VOLUME
TREBLE
BASS

Fig.55. Don't rely on engineer friends to test your musical designs. Use real musicians, they will find weaknesses quickly, such as these easily snapped plastic shaft pots.

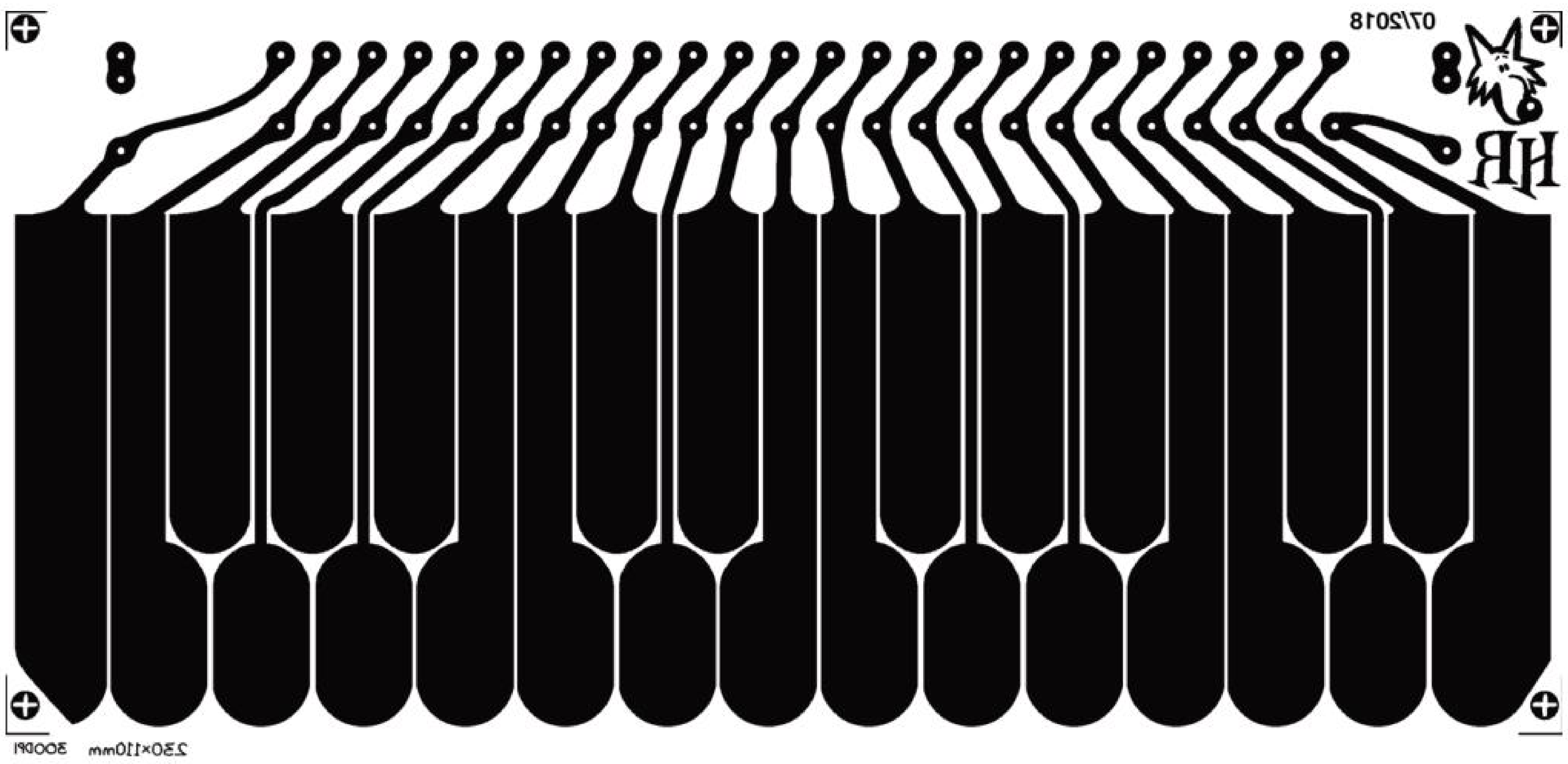


Fig.56. Shown half size, a suggested pattern for the keyboard, designed by Harvey Rothman. Remember that the copper side is the top of the board. (Design available from EPE website.)

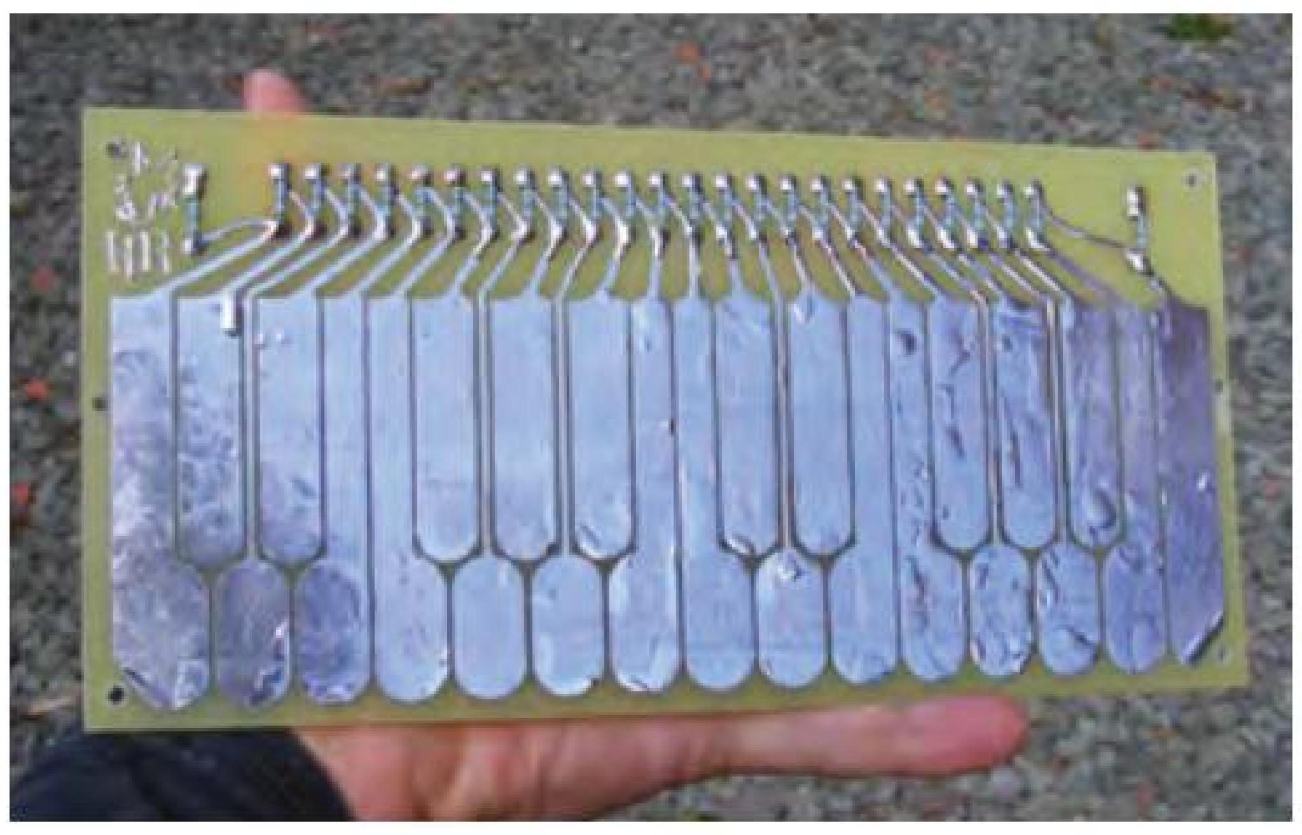


Fig.57. The finished keyboard – the copper must be tinned to prevent oxidation, and remember to flux it first.

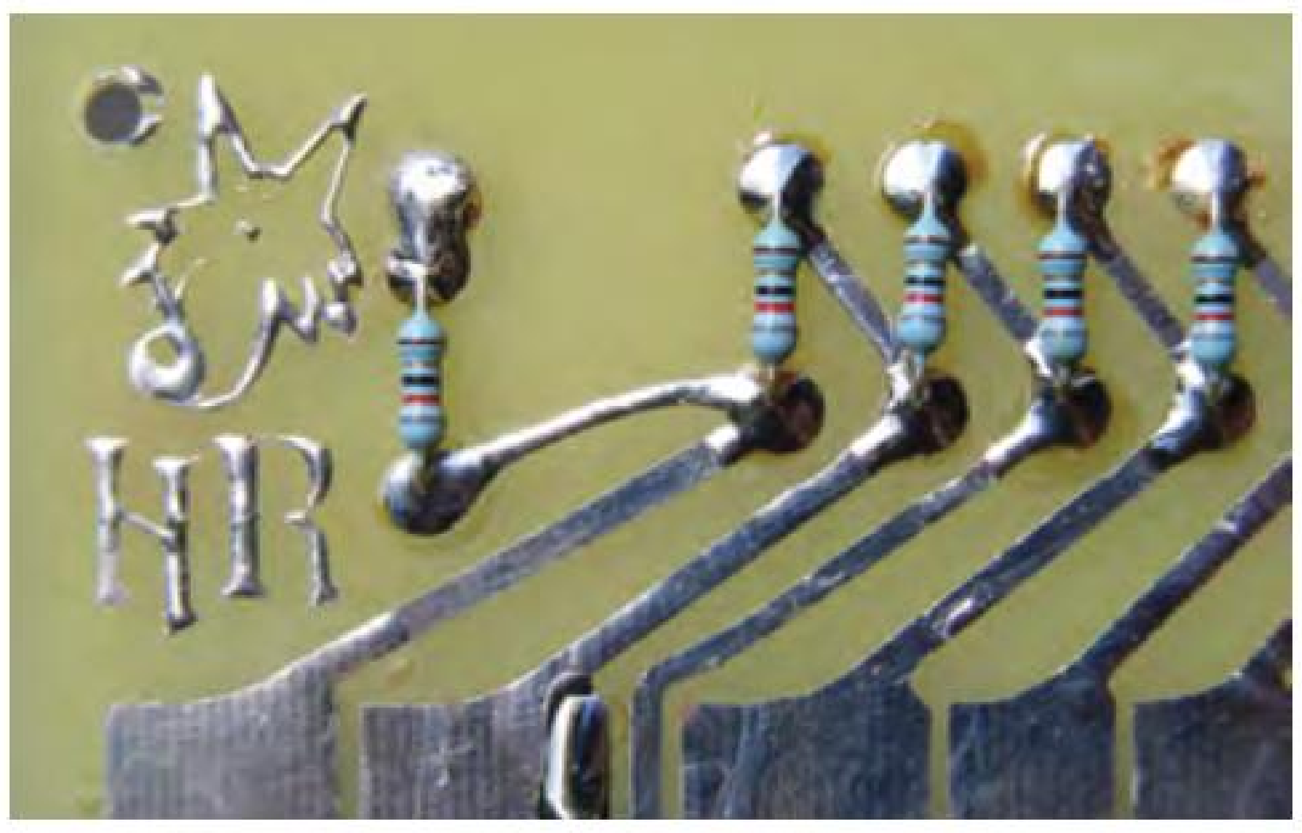
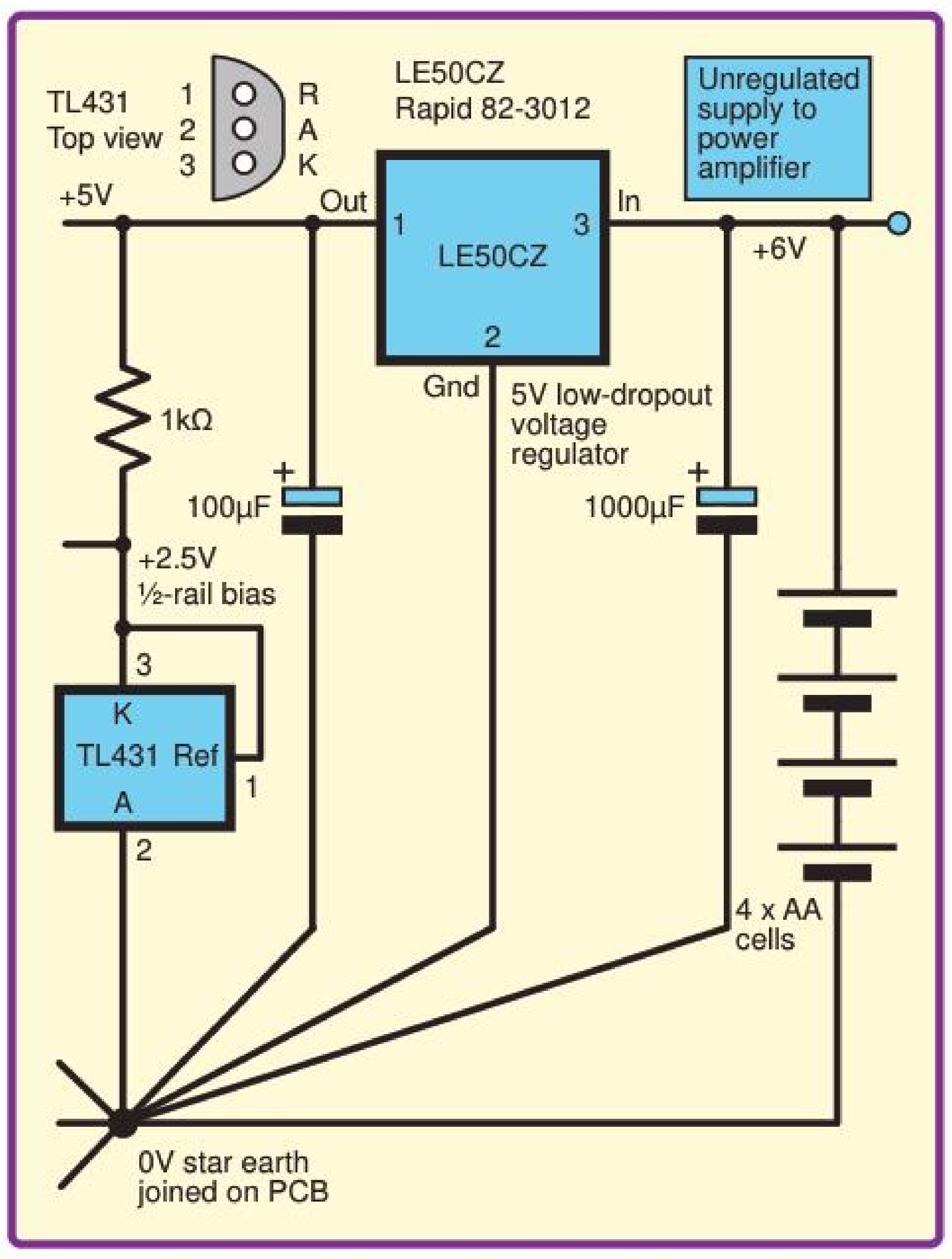


Fig.58. A close-up of the resistors mounted on the copper side.

It can be scaled to a size that suits you. The file will be available on the *EPE* website. This pattern is suitable for both the 1V/octave and twelfth-root-of-two circuits. The completed keyboard is shown in Fig.57 and the resistor wiring is illustrated in Fig.58.

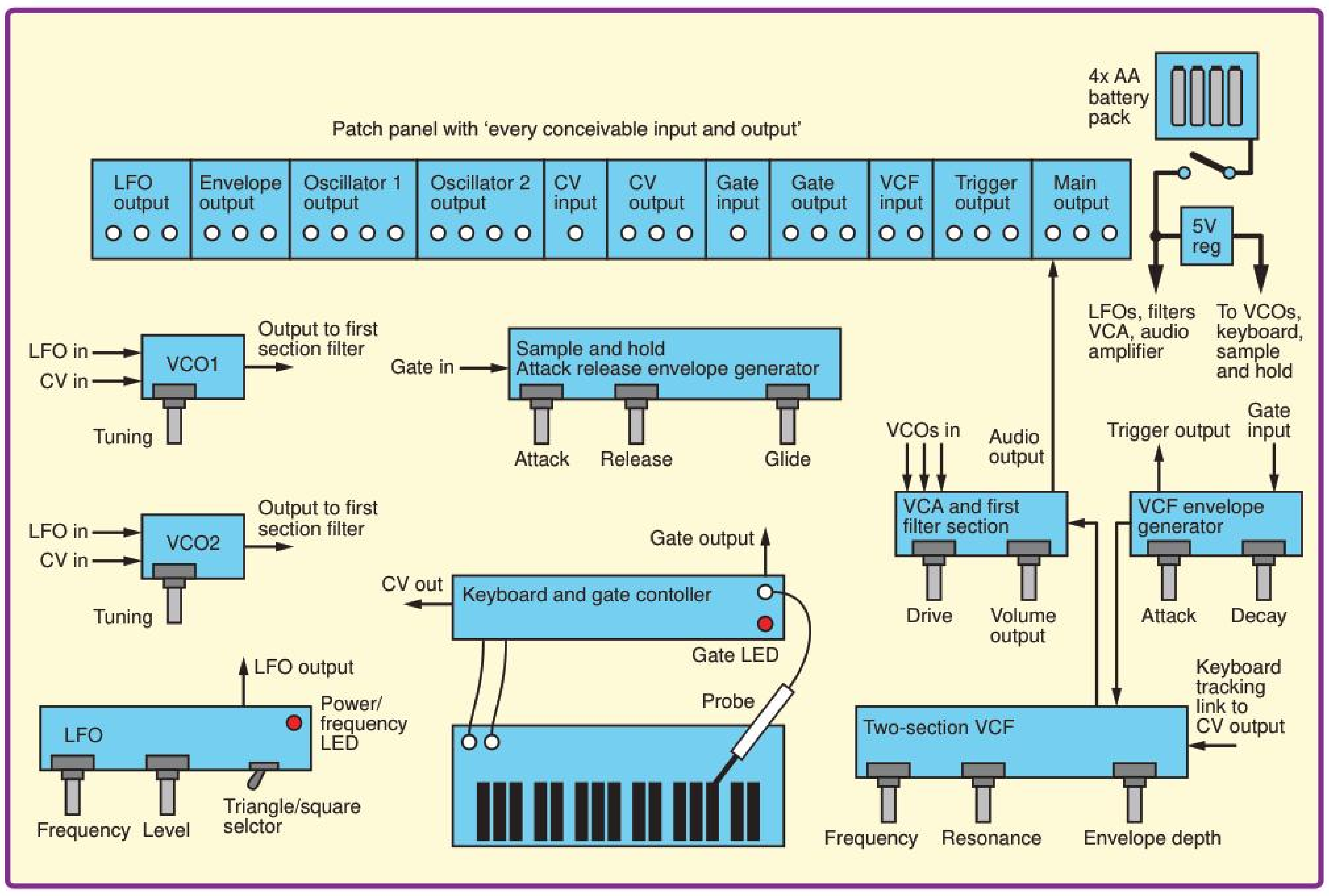
Voltage regulators

Oops, confession time! – I got the pinout wrong on the TL431 shunt regulator used in the power supply circuit (Fig.4, *Part 1*). The circuit diagram is repeated in Fig.59, but corrected. In fact, I decided against using it because each board has its own individual bias circuit – but it's important that errors are corrected. The 5V regulator of choice is now a LD50CZ in a standard TO92 leaded package; the circuit is shown in Fig.59.



TL431
Top view
1 2 3
R A K
LE50CZ
Rapid 82-3012
Unregulated supply to power amplifier
+5V
Out
1
LE50CZ
3
In
2
Gnd
+6V
1kΩ
100µF
5V low-dropout voltage regulator
1000µF
+2.5V
½-rail bias
3
K
TL431 Ref
A
1
2
4 x AA cells
0V star earth joined on PCB

Fig.59. Revised Fig.5, Part 1. The originally quoted half-rail regulator isn't used any more, but at least the pinout is now correct!



4x AA battery pack
Patch panel with 'every conceivable input and output'
LFO output
Envelope output
Oscillator 1 output
Oscillator 2 output
CV input
CV output
Gate input
Gate output
VCF input
Trigger output
Main output
5V reg
LFOs, filters VCA, audio amplifier
To VCOs, keyboard, sample and hold
LFO in
CV in
VCO1
Output to first section filter
Tuning
Gate in
Sample and hold
Attack release envelope generator
Attack
Release
Glide
VCOs in
Audio output
Trigger output
Gate input
LFO in
CV in
VCO2
Output to first section filter
Tuning
Gate output
VCA and first filter section
VCF envelope generator
CV out
Keyboard and gate contoller
Drive
Volume output
Attack
Decay
Gate LED
LFO output
Power/ frequency LED
Probe
Keyboard tracking link to CV output
LFO
Two-section VCF
Frequency
Level
Triangle/square selctor
Frequency
Resonance
Envelope depth

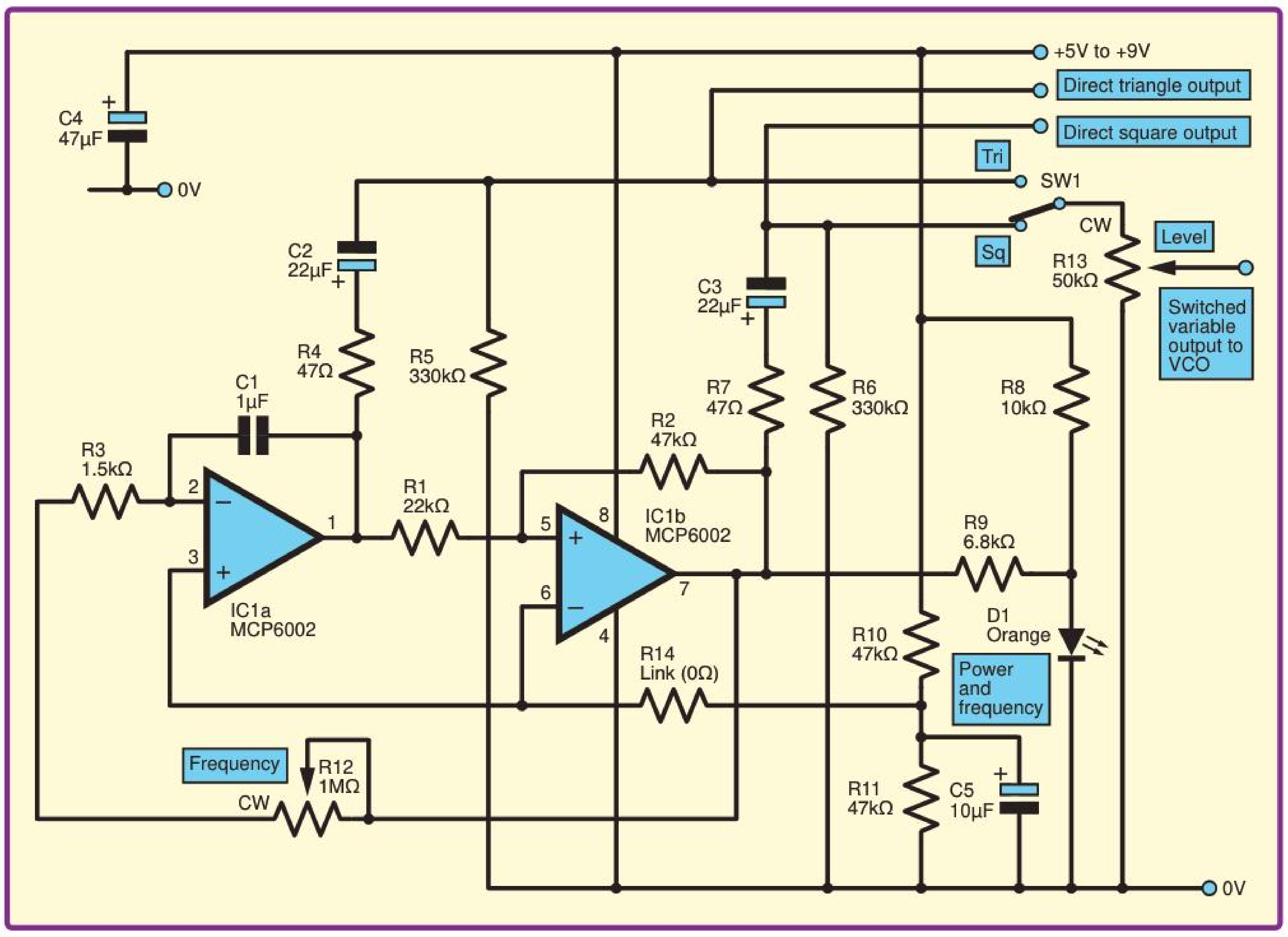
Fig.60. Block diagram of the synthesiser shown in Fig.54.

On the Gen X-1 it was essential to have a low-impedance regulated centre-rail bias supply because it supplied all the bias references. The use of large decoupling capacitors also helps keep the voltage stable. This prevented thumps produced by the subsonic modulation frequencies used.

Another useful idea for low-voltage, battery-powered equipment is to power circuits that don't need a regulated supply directly from the battery – for example, the gate circuit and the power amplifier. This gives maximum headroom and minimises fluctuating loads on the regulator for better VCO stability. I have also found with 5V single-rail, low-power analogue circuits that the theoretical 2.5V bias is not necessarily optimum. Therefore, all the circuits here have their own bias networks. In a modular system it's one less wire and one less cause of total failure. The current consumption for the whole synth is around 10mA, about a tenth of other similar synth circuit designs I have seen. The block diagram of the system is shown in Fig.60, although this is only a suggested patch because the user can connect their own modules together as required. The pre-PCB Veroboard prototype is shown in Fig.54.

Low-frequency oscillator

The low-frequency oscillator is the simplest module, so that's where we'll start – see the circuit in Fig.61. This is basically the circuit described previously (Fig.13, *Part 1*) but with a switch added for triangle/square output and a level potentiometer. The potentiometer is logarithmic to allow subtle vibrato adjustments at low level and over-the-



+5V to +9V
Direct triangle output
Direct square output
Tri
SW1
Sq
CW
Level
C4 47µF
0V
C2 22µF
C3 22µF
R13 50kΩ
Switched variable output to VCO
R4 47Ω
R5 330kΩ
R7 47Ω
R6 330kΩ
R8 10kΩ
C1 1µF
R2 47kΩ
R3 1.5kΩ
2
3
1
R1 22kΩ
5
8
IC1b MCP6002
6
7
4
R9 6.8kΩ
IC1a MCP6002
D1 Orange
R10 47kΩ
R14 Link (0Ω)
Power and frequency
Frequency
R12 1MΩ
CW
R11 47kΩ
C5 10µF
0V

Fig.61. Circuit for the low-frequency oscillator (LFO).

top octave modulation at full rotation. I have also changed the frequency potentiometer in Fig.13, *Part 1* from 220kΩ to 1MΩ, and the integrator capacitor from 150nF to 1µF to give a lower minimum frequency sweep. The output has to be AC coupled, which gives a unique sonic effect due to differentiation of the square-wave.

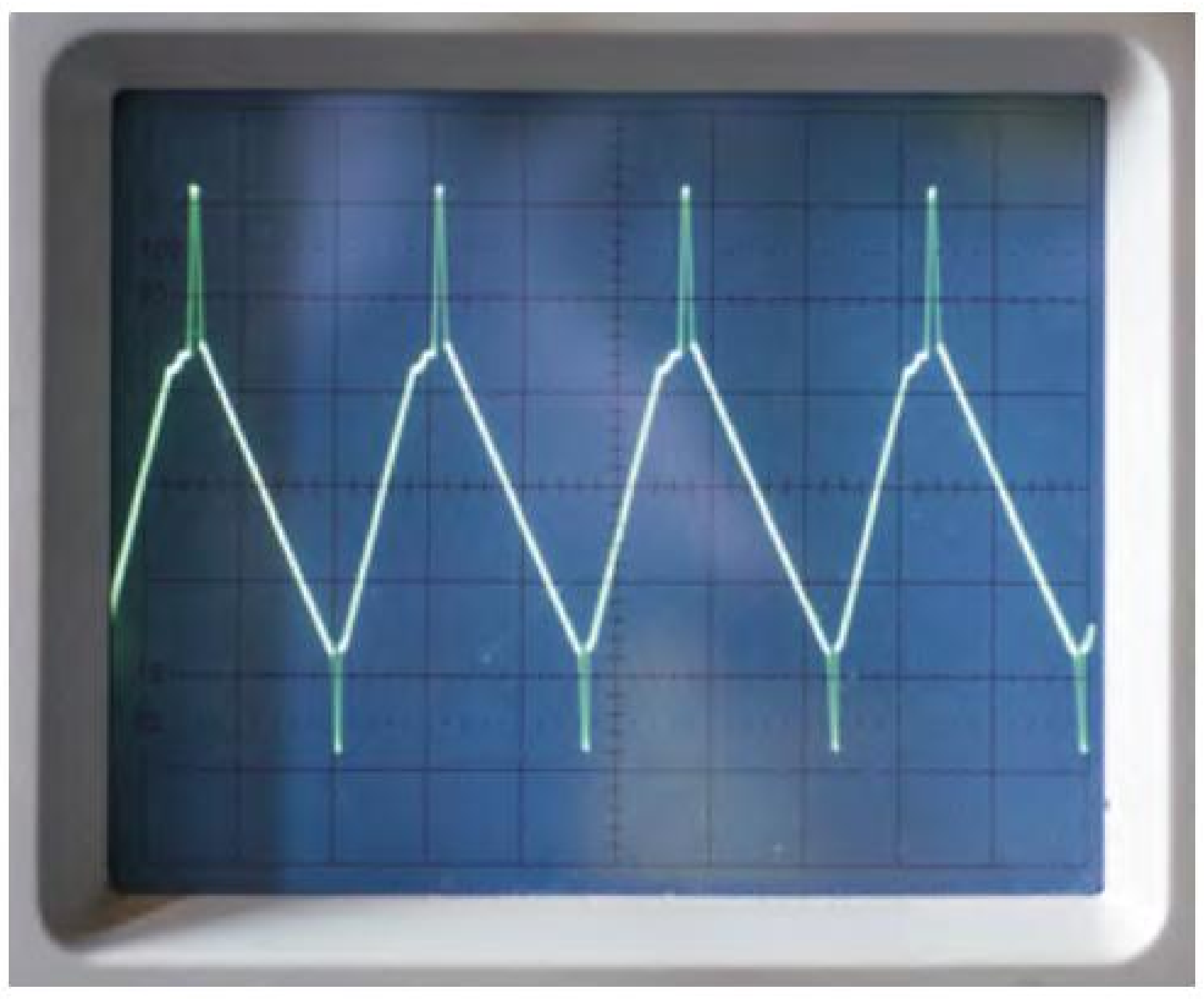


Fig.62. Triangle waveform of LFO using LM358 op amp (Photo: Harvey Rothman).

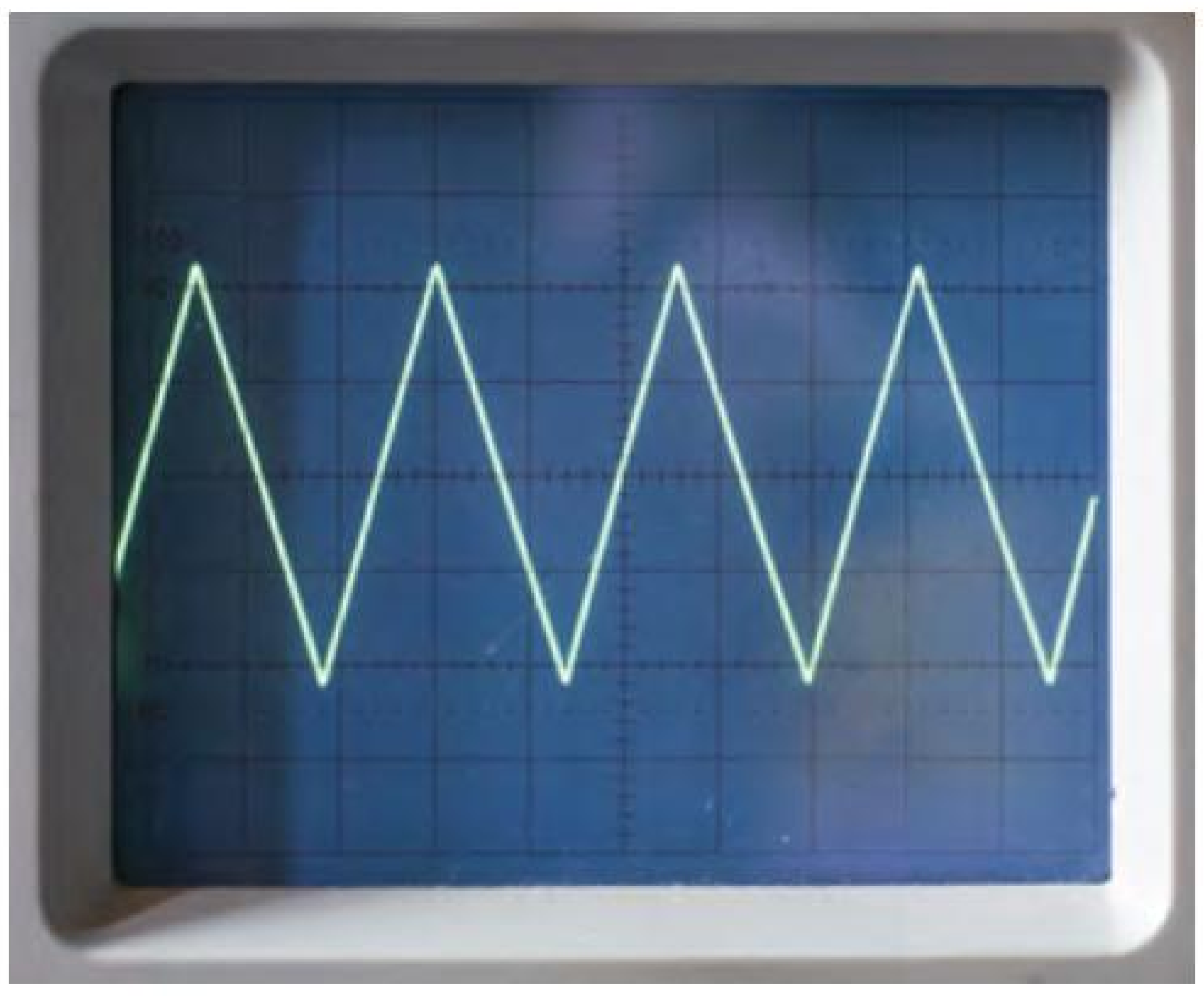


Fig.63. LFO using an MCP6002 op amp, instead of the LM358. The result is more output and a cleaner waveform (Photo: Harvey Rothman).

The square wave output is twice that of the triangle. I thought this would be a problem when doing the switching, but I found it was desirable to have a higher square-wave modulation level, since it is often used to flip between two extreme notes. Making a synthesiser operate like a piece of test gear so that it looks perfect on the 'scope often gives a dull sound. If there's a glitch that sounds good, then keep it!

Components

The standard op amps used for battery-operated music equipment are the bipolar LM358 and Bi-Fet TL062. A superior chip I have found, is the MCP6002 from Microchip (of PIC fame), which I used in the Gen X-1. It works down to 3V and has rail-to-rail input/output capability. This uses MOSFET technology, similar to the old CA3140, but without the instability. They cost 25p from RS (403-036). The current consumption is 0.2mA at 5V, compared to 0.45mA for the LM358 and 0.32mA for the TLO62. The difference is clearly apparent in Fig.62 and Fig.63.

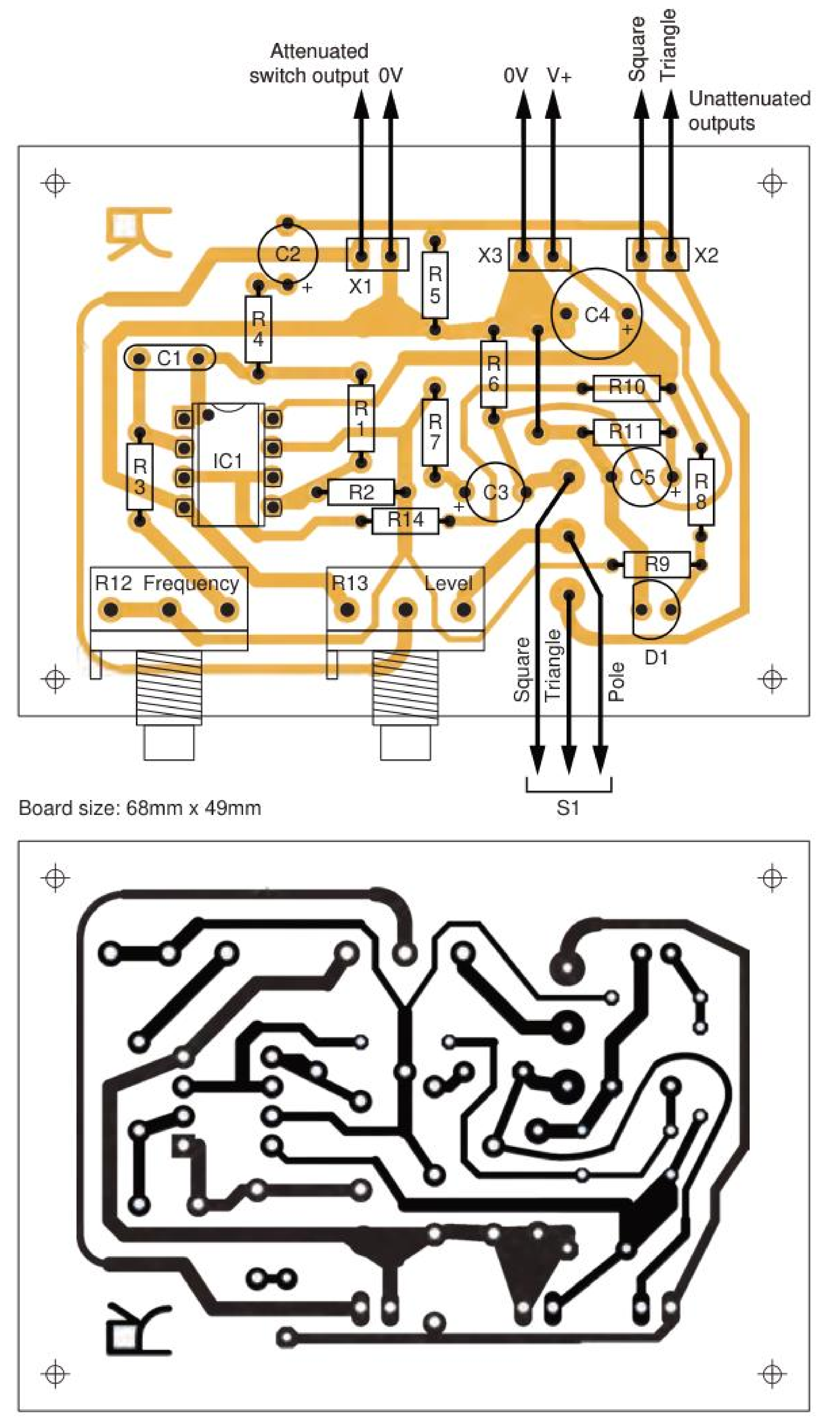


Fig.64. LFO PCB layout – for design file see box at end of article.

The LED doubles as a frequency and power-on indicator; it's normally dimly lit, pulsing with the LFO frequency. I use a special orange LED from Kingbright L-7104SEC (Rapid, 72-8972) which gives excellent brightness at 1mA. I've come across a lot of battery equipment where the LED uses more current than the circuit!

The toggle switch is a bit unusual (centre off), because it is useful to flip down when a preset modulation level is required for live performance. It's most useful to have triangle in the down position for turning vibrato on and off with the thumb. Unfortunately, so far I've failed to source the PCB-mount C&K switch I found in my 'junk box'. That means we'll need to hard-wire the specified switch on later boards.

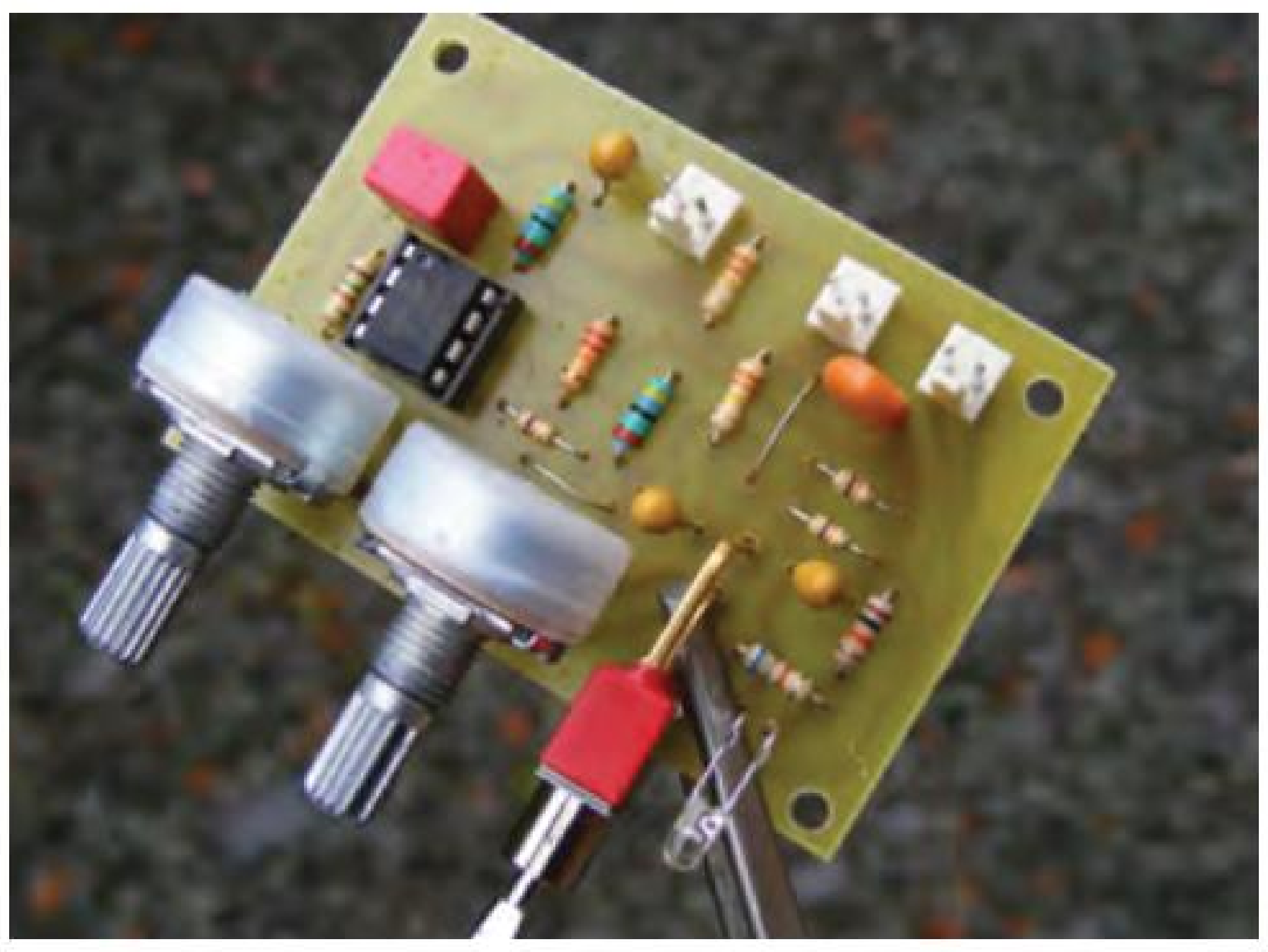


Fig.65. The completed LFO.

Modulation mayhem

The LFO is a cheap circuit, and we need several of them to modulate in different parts of the synthesiser, so it's a good idea to use separate ones for the VCO, VCF and VCA for a constantly changing sound. This is why there is only one level pot on the PCB. The layout is shown in Fig.64, and the finished board in Fig.65. Fellow Dutch synthesiser designer Rob Hordijk says, 'modulate everything with everything' (see **synthtopia.com**). This is where modular synthesisers excel, you just need enough plugs and sockets to connect them all up like Lego. Unfortunately, 3.5mm jack plugs seems to be standard today – the curse of miniaturisation has now come to synths. I liked Don Buchla's system of banana plugs since it's easy to stack plugs on top of each other (Don was the other original pioneer of synthesiser design, less well known than Bob Moog, but just as influential).

Parts list – Low-frequency oscillator

Resistors

R1 22kΩ
R3 1.5kΩ
R5, R6 330kΩ
R9 6.8kΩ
R2, R10, R11 47kΩ
R4, R7 47Ω
R8 10kΩ
R11 0Ω link

Capacitors

C1 1µF film 5mm
C2, C3 22µF electrolytic 5mm
C4 47µF
C5 10µF

Semiconductors

IC1 MCP6002 dual MOSFET op amp, RS 403-036
D1 orange 3mm LED high efficiency, Kingbright L-7104SEC, Rapid 72-8972

Miscellaneous

SW1 Centre-off latching SPDT toggle switch from SCI, Rapid 75-0135

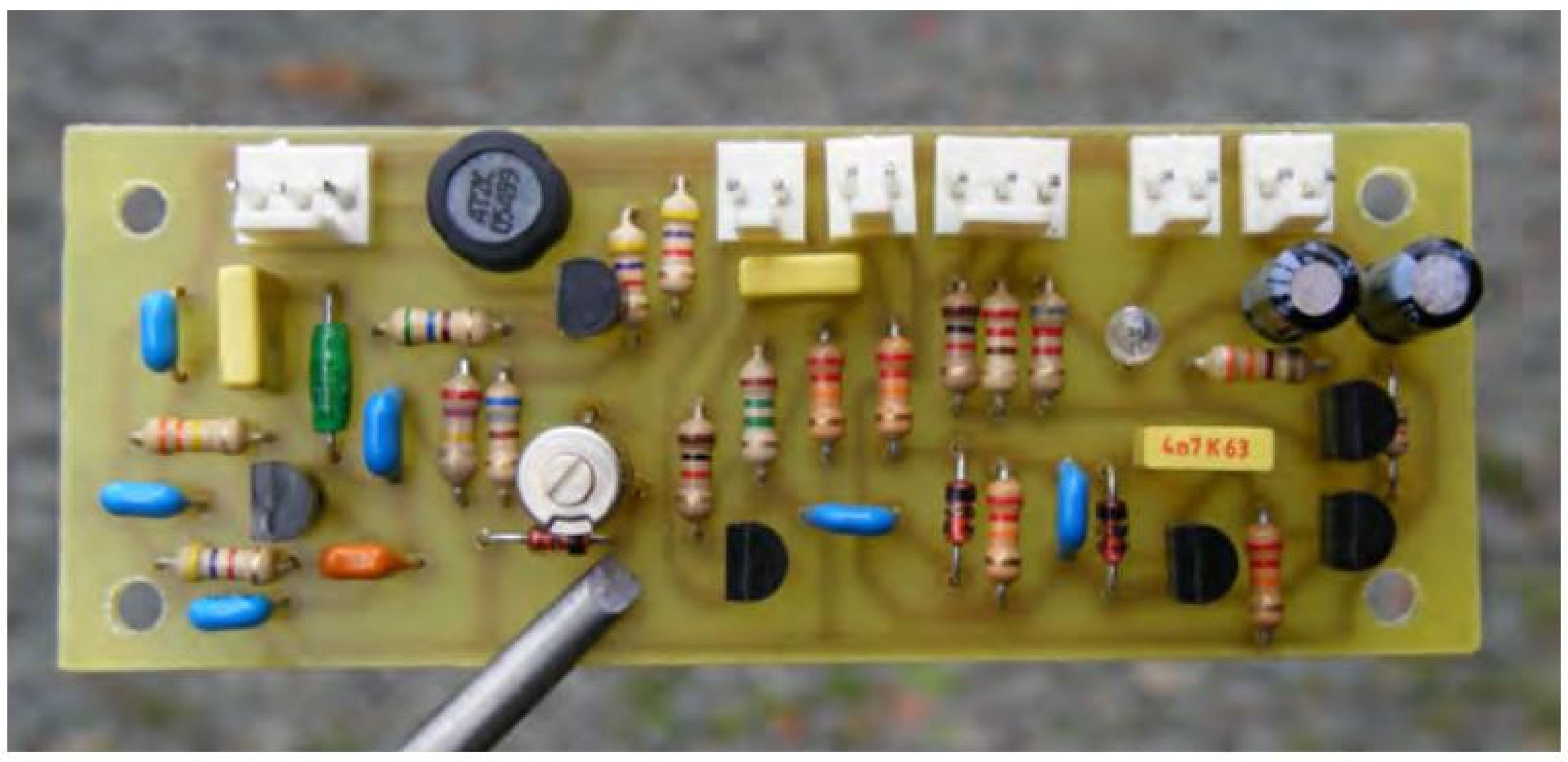


Fig.66. Completed keyboard controller and gate generator board.

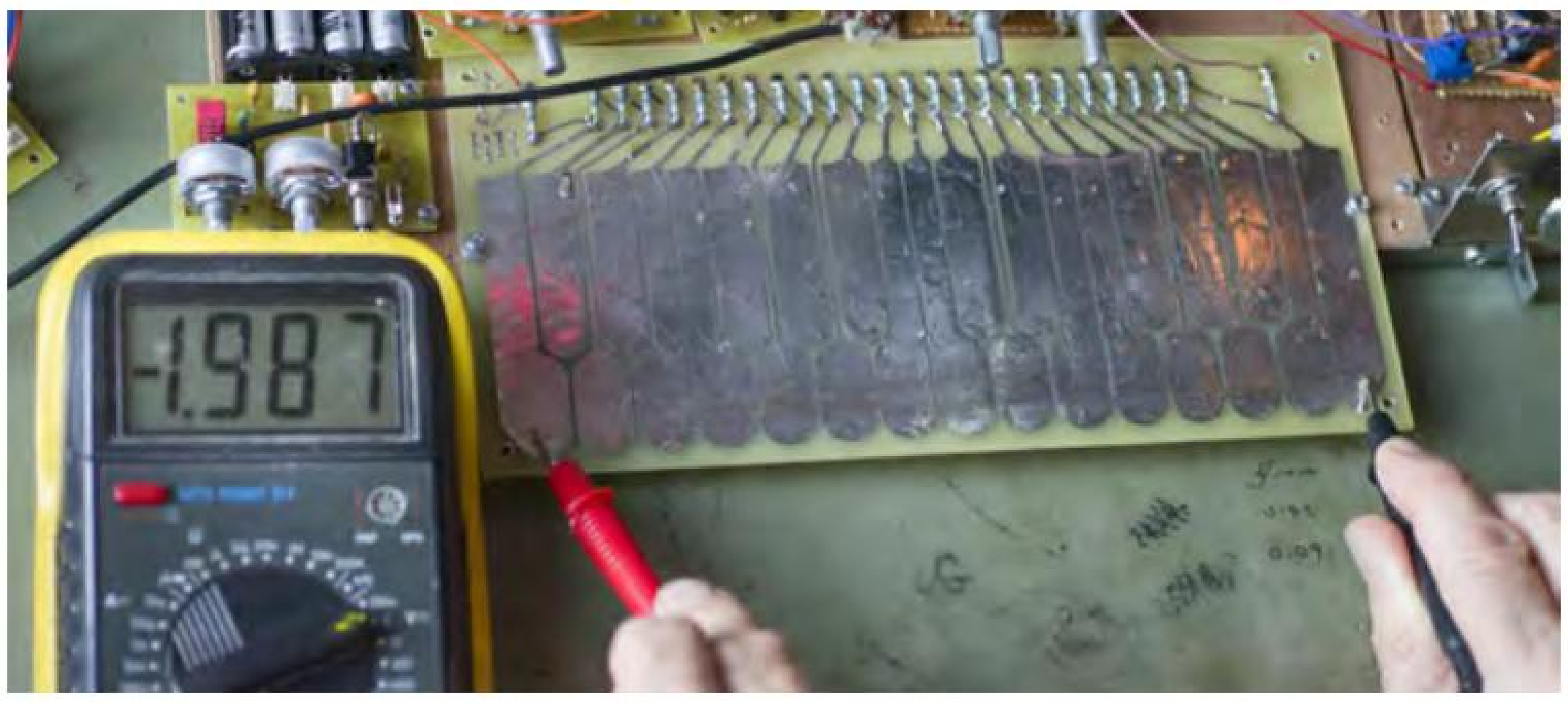


Fig.67. It's easy to measure the voltage across the keyboard. Just adjust the current so it measures 2V.

Molex 3-way header, 3 off, Rapid 22-0955
PCB ref. AO-1018-01

Keyboard and gate generator

Two Veroboard circuits from *Part 2*, the keyboard voltage generator (Fig.36) and the high-frequency detector gate generator (Fig.38) have been combined into a single PCB shown in Fig.66. One minor improvement here is to replace one of the reference diodes with a trimmer (R4) to set the keyboard voltage to exactly 2V across the two octaves, or 83mV between each note. If this were a production model then I would get rid of the preset by using an op-amp-based current source. One advantage of the Stylophone-style keyboard is that meter probes in test mode can be directly be placed on it, as shown in Fig.67. This circuit gives low-note priority because the keyboard shorts to the lower resistor when two notes are played together.

Gate circuit

I have combined and revised the two circuits shown in Fig.36 and Fig.38 – see Fig.68, which will be used with a unique opto-FET sample-and-hold circuit described later. Referring to the original circuit (Fig.38, *Part 2*), the final inverter stage has been omitted and the voltage doubler diode D3 goes to the other side of the junction of D1 and C9. The PCB layout is shown in Fig.69. Suitable coils are available from Mouser, but are not critical, we are not building a radio or switch-mode power supply.

Parts list – Keyboard controller and gate circuit

Resistors
R1 330kΩ R2, R6, R7 4.7kΩ
R3 270kΩ R4 2kΩ R5 220Ω
R8 560Ω R9, R18 1kΩ
R10, R12, R13, R16 22kΩ
R14 100Ω R15 8.2kΩ
R17 47kΩ R19 330Ω

Capacitors
C1, C2, C5 100nF X7R ceramic 5mm
C3 680pF NPO or film 5mm
C4 2200pF NPO ceramic or film 5mm
C6, C10 10nF X7R ceramic 5mm
C7 1nF X7R ceramic 5mm
C8 47µF electrolytic 5mm
C9 22nF polyester 5mm
C12 4.7nF X7R ceramic or film 5mm

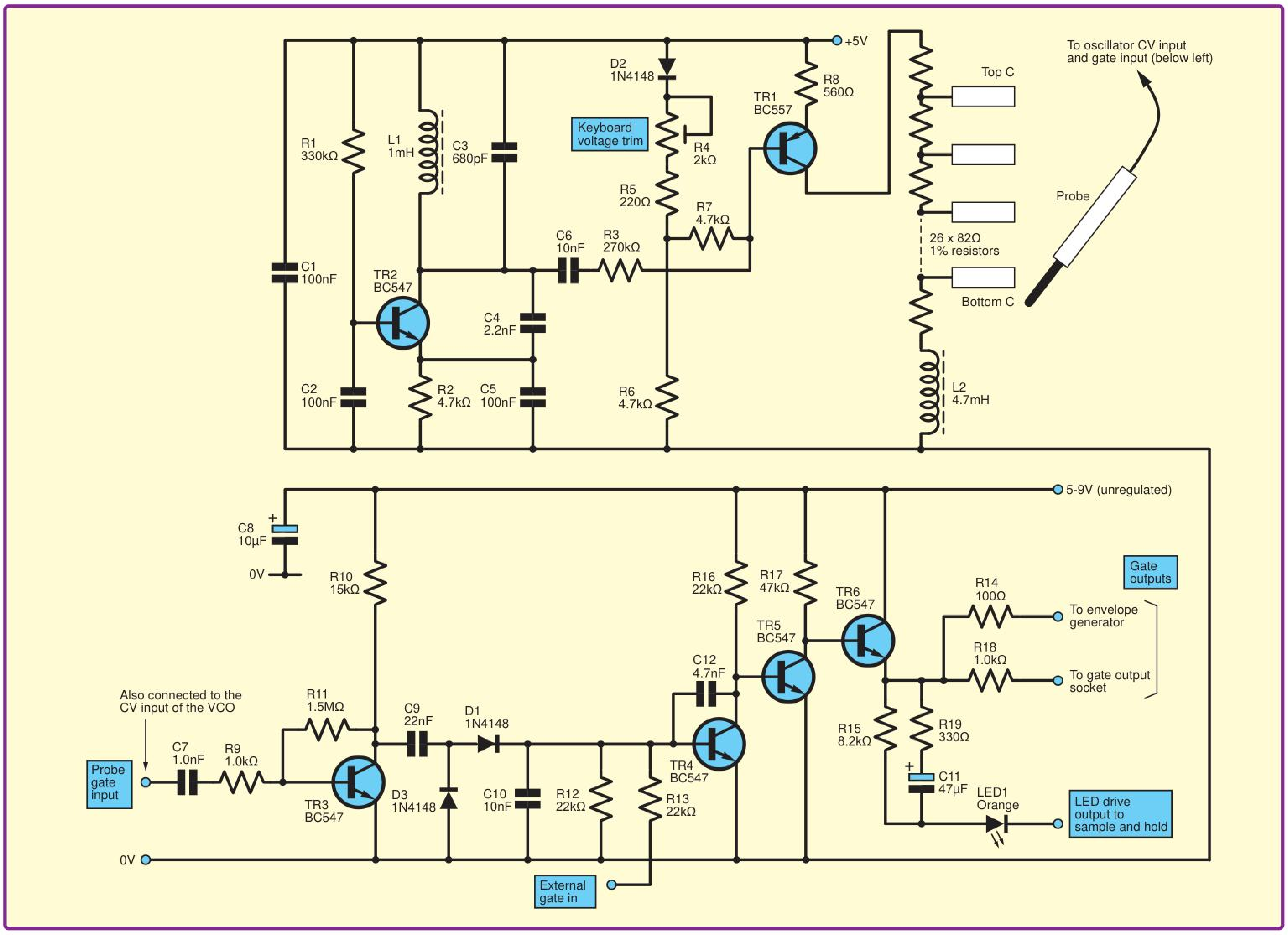

+5V
D2 1N4148
R8 560Ω
TR1 BC557
Keyboard voltage trim
R4 2kΩ
R1 330kΩ
L1 1mH
C3 680pF
R5 220Ω
R7 4.7kΩ
C6 10nF
R3 270kΩ
C1 100nF
TR2 BC547
C4 2.2nF
C2 100nF
R2 4.7kΩ
C5 100nF
R6 4.7kΩ
Top C
26 x 82Ω 1% resistors
Bottom C
L2 4.7mH
To oscillator CV input and gate input (below left)
Probe
5-9V (unregulated)
C8 10µF
0V
R10 15kΩ
R16 22kΩ
R17 47kΩ
TR6 BC547
TR5 BC547
Gate outputs
R14 100Ω
To envelope generator
R18 1.0kΩ
To gate output socket
C12 4.7nF
Also connected to the CV input of the VCO
R11 1.5MΩ
C9 22nF
D1 1N4148
TR4 BC547
R15 8.2kΩ
R19 330Ω
C11 47µF
LED1 Orange
LED drive output to sample and hold
Probe gate input
C7 1.0nF
R9 1.0kΩ
TR3 BC547
D3 1N4148
C10 10nF
R12 22kΩ
R13 22kΩ
0V
External gate in

Fig.68. The combined keyboard controller and gate generator circuit. The gate circuit is run off the unregulated supply.

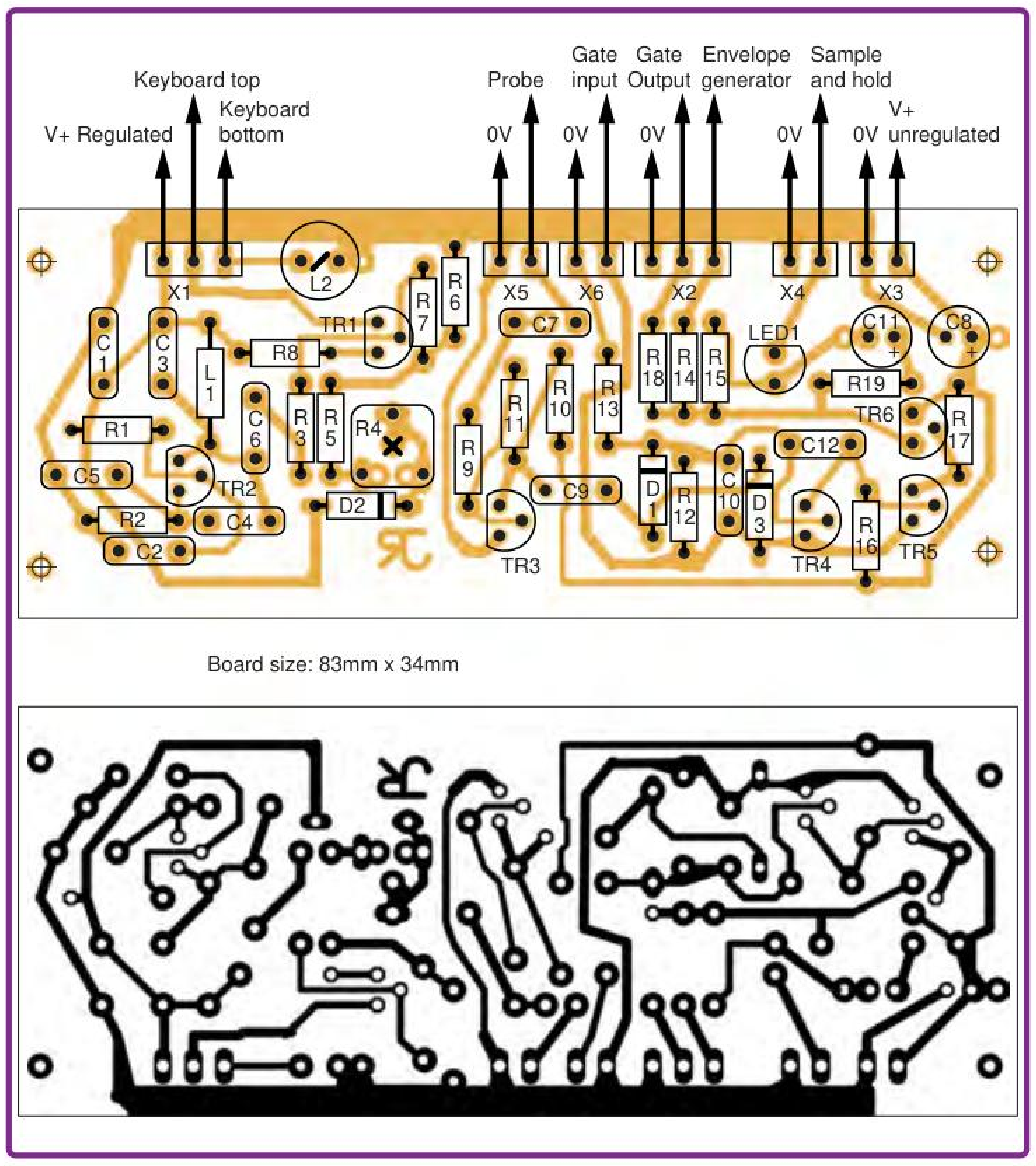

Keyboard top
Keyboard bottom
V+ Regulated
Probe
Gate input
Gate Output
Envelope generator
Sample and hold
V+ unregulated
0V
X1
X5
X6
X2
X4
X3
L2
TR1
R8
R7
R6
C7
LED1
C11
C8
R19
TR6
R17
C12
C9
D2
TR2
TR3
TR4
TR5
R1
C5
R2
C4
C2
C1
C3
L1
C6
R3
R5
R4
R9
R11
R10
R13
R18
R14
R15
D1
R12
C10
D3
R16
Board size: 83mm x 34mm

Fig.69. Keyboard circuit PCB – see PCB box at end of article.

Semiconductors
LED1 orange 3mm high-efficiency Kingbright L-7104SEC, Rapid 72-8972
D1 to D3 1N4148
TR1 BC557, BC212 PNP (or other common generic examples)
TR2 to TR6 BC547, BC182 NPN (or other common generic examples)

Inductors
L1 1mH axial, Sigma SC30, Fastron MICC-102K-02, Rapid 88-2815
L2 4.7mH Radial, Murata 22R475C 3mm from Mouser or Murata 262LY-472K 8RBS series 5mm from Farnell (now discontinued)
PCB ref. AO-1018-02

Buffering the VCO

Unwanted interactions are the bane of analogue circuits and the solution in most cases is buffering, using an amplifier with unity gain to provide isolation. The VCO exponentiator given earlier (Fig.21, *Part 1*) can be improved by buffering the 1.7V voltage reference. (Please also note that R8 is redundant and only R10 is necessary on the original circuit in Fig.21). This voltage was found to vary slightly with frequency. In conjunction with the decoupling capacitor, an audible bounce occurred when going from the highest to the lowest note. Buffering the tuning control voltage also reduced minor scaling changes. These improvements only added one dual op amp. The revised circuit of the complete VCO and exponentiator is shown in Fig.70. The PCB layout is shown in Fig.71 and a completed module in Fig.72. Note how the thermistor R20 and exponentiator transistors TR1 and TR2 are all placed close together, so they remain at the same temperature.

Parts list – VCO

Resistors
All resistors 5% carbon film 0.25W unless otherwise stated.
R1 56Ω R2 22kΩ R3 2.2kΩ
R4 100Ω R5 100kΩ
R6 100kΩ 1% 0.25W metal-film
R7 56kΩ1% 0.25W metal-film
R8 50kΩ Linear 16mm pot
R9 20kΩ R10 5.1kΩ
R11 47kΩ R12 10kΩ
R13 25kΩ R14 33kΩ
R15 150kΩ R16 27kΩ
R17 Link R18 3.3kΩ
R19 470kΩ 1% 0.25W metal-film
R20 1kΩ **mouser.co.uk** (PTCLT300014T261K0J)

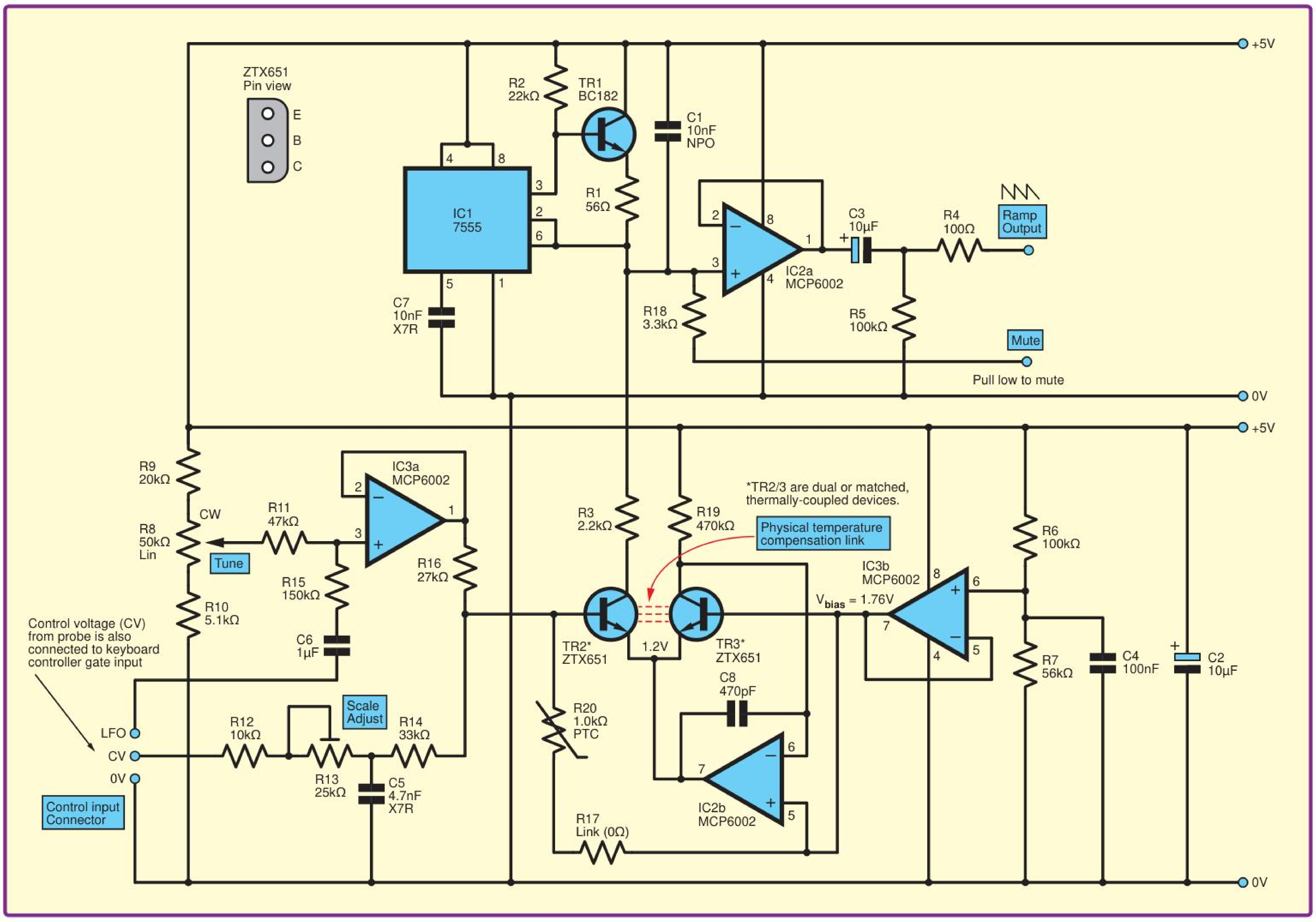

+5V
ZTX651 Pin view
E
B
C
R2 22kΩ
TR1 BC182
C1 10nF NPO
IC1 7555
4
8
3
2
6
5
1
R1 56Ω
C7 10nF X7R
R18 3.3kΩ
IC2a MCP6002
C3 10µF
R4 100Ω
Ramp Output
R5 100kΩ
Mute
Pull low to mute
0V
+5V
R9 20kΩ
IC3a MCP6002
R8 50kΩ Lin
CW
Tune
R11 47kΩ
R15 150kΩ
R16 27kΩ
R10 5.1kΩ
C6 1µF
Control voltage (CV) from probe is also connected to keyboard controller gate input
LFO
CV
0V
Control input Connector
R12 10kΩ
Scale Adjust
R14 33kΩ
R13 25kΩ
C5 4.7nF X7R
R3 2.2kΩ
R19 470kΩ
*TR2/3 are dual or matched, thermally-coupled devices.
Physical temperature compensation link
TR2* ZTX651
1.2V
TR3* ZTX651
C8 470pF
R20 1.0kΩ PTC
IC2b MCP6002
R17 Link (0Ω)
IC3b MCP6002
V_bias = 1.76V
R6 100kΩ
R7 56kΩ
C4 100nF
C2 10µF
0V

Fig.70. The voltage-controlled oscillator circuit and associated exponentiator, a unique ultra-low-power design.

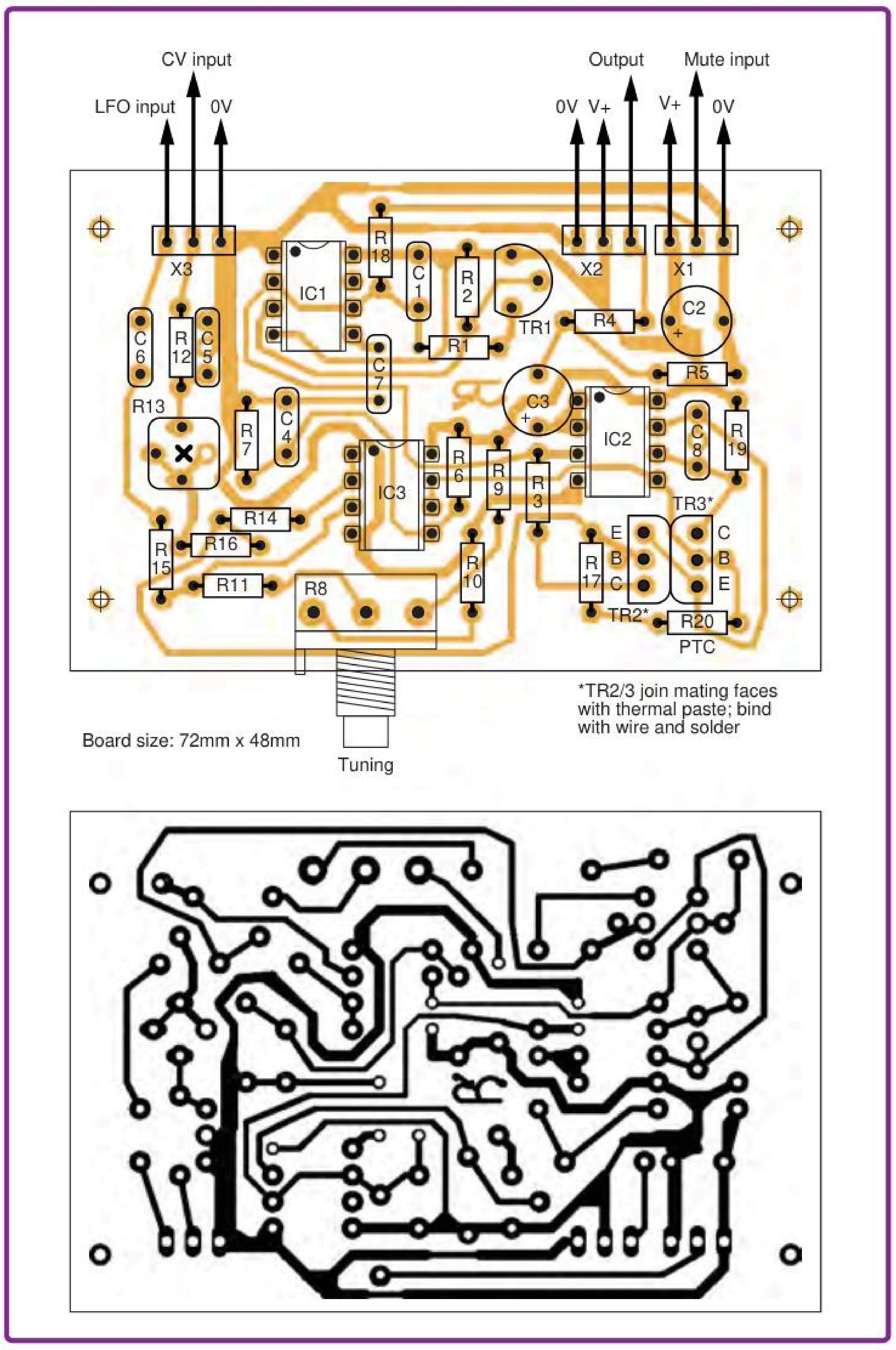


Fig.71. VCO PCB layout – see PCB box at end of article.

Capacitors
C1 10nF NPO, 5% 5mm (**mouser.co.uk** FG28C0G1H103JNT06)
C2, C3 10uF 10V radial electrolytic 5mm
C4 100nF ceramic X7R
C5 4.7nF ceramic X7R
C6 1µF polyester 5mm
C7 10nF ceramic X7R
C8 470pF ceramic X7R

Semiconductors
IC1 7555 CMOS timer
IC2, IC3 MCP6002 MOSFET dual op amp (RS 403-036)
TR1 BC182
TR2, TR3 ZTX651 Matched V_{be} pair
Molex 3-way 0.1-inch header, 3 off
PCB ref. AO-1018-03

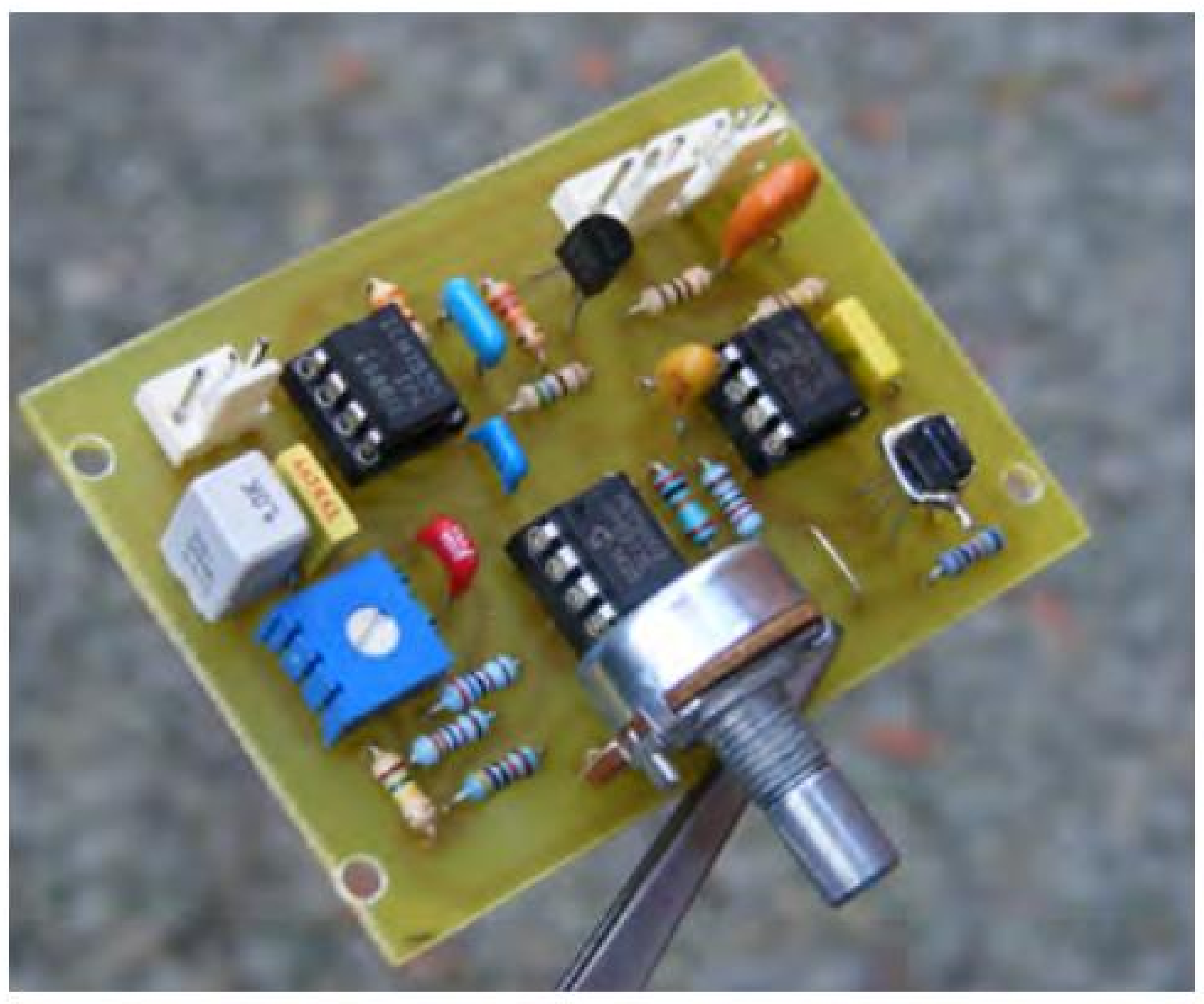


Fig.72. The completed VCO.

Matching transistors

In the end, the SMT components were abandoned due to a lack of thermal mass; the slightest drought upset them despite being well matched. I'm going to try using a large area of PCB ground plane next time. Surprisingly, a hand-matched pair of thermally bonded ZTX651 transistors (from a company called Diodes Incorporated, formerly Ferranti) worked better. These are small power devices that have an $I_{c,max}$ of 2A. They are available from Rapid (81-0224), and 20 for £1 at J Birkett's, Lincoln. A 1kΩ 3000ppm/°C resistor provided the compensation. I'm not sure why this combination worked best, it was determined empirically – good old trial and error! The transistors have to be accurately matched for V_{be}, within a few mV for accurate thermal cancellation. If one transistor has a greater V_{be} than the other then its thermal drift will dominate.

Matching techniques

A simple matching circuit for V_{be} is shown in Fig.73. The current sink can be a standard 1mA constant-current diode or a variable one built around a FET or op amp. H_{fe} matching is not especially important since the circuit impedances are low. Better still, plot curves of I_c verses V_{be} using a Peak DCA75 analyser connected to a PC. I will go into this in a little more detail next month.

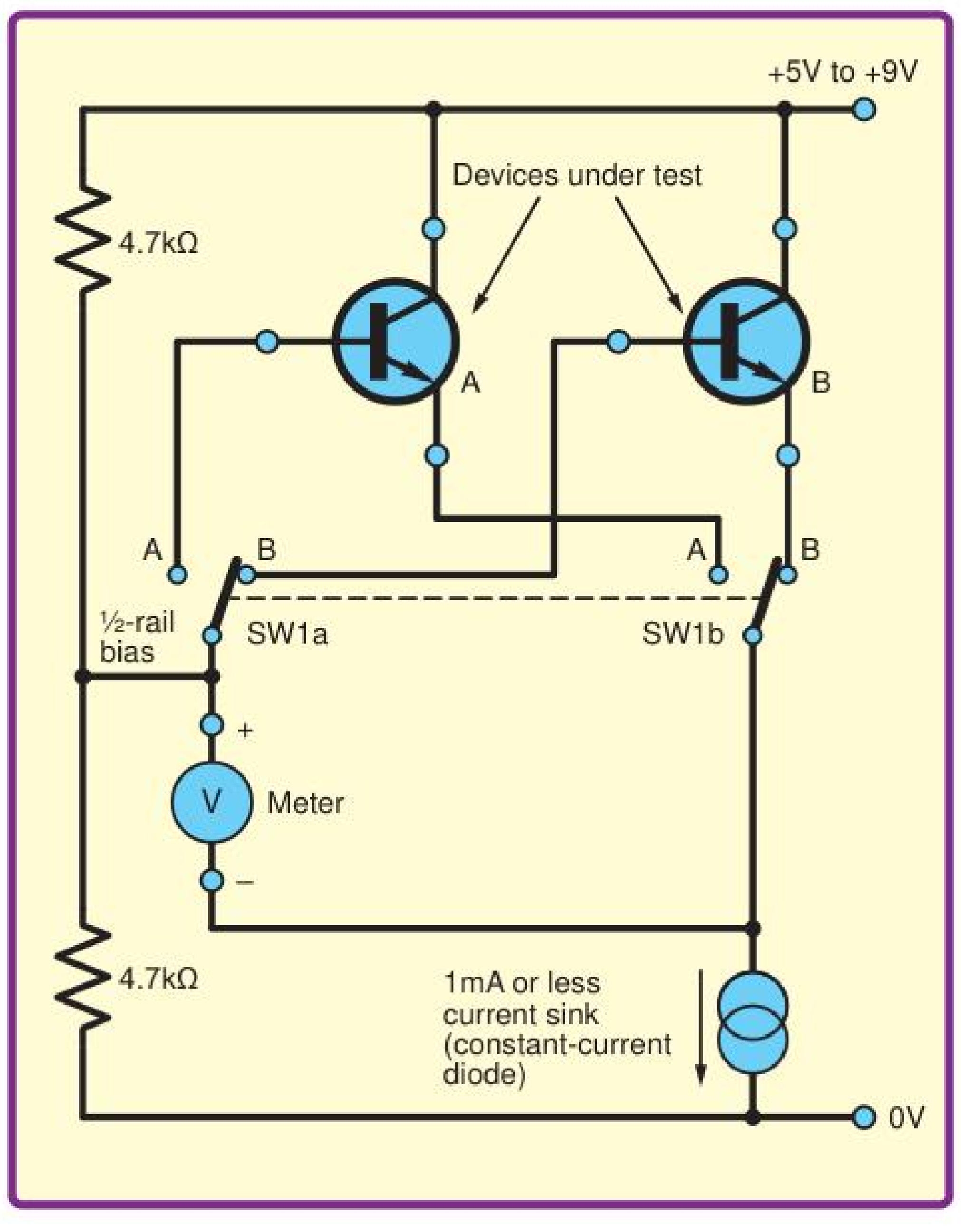


Fig.73. Simple transistor-matching circuit for comparing the V_{be} values of two transistors.

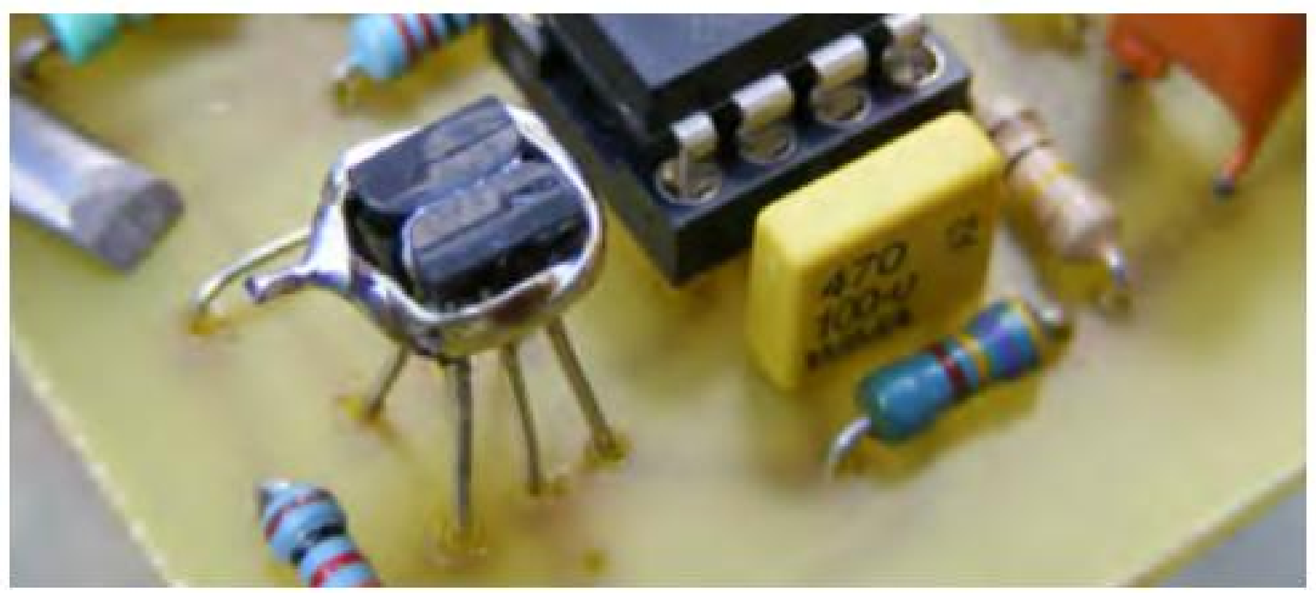


Fig.74. ZTX651 transistors installed on the VCO board – note device orientation.

Getting clamped

The clamping of the transistors on the PCB may look wrong given that the sides with curved corners are facing each other, but the thermal resistance is less on that side. The trick is to twist 26 SWG wire around them with heatsink compound on the mating surfaces and then solder it to aid rigidity. A close up is shown in Fig.74. The exponentiator transistors are the only critical bipolar transistors in the circuit – 'bog-standard' ones, such as BC108, BC549 and 2N3904 can be used elsewhere. The single PNP device could be a 2N3906 or a BC559.

Tuning up

Every transistor has a different V_{be} for a given collector current so it is essential to adjust the oscillator so that it actually operates at 1V/octave. This is the function of the scale preset R13. Once the keyboard voltage has been set correctly this trimmer has to be adjusted so the octaves are correct on the keyboard.

Dual oscillators

When the scaling is set up another oscillator can be added in parallel (they must track each other). Two oscillators sound much better than one – a pair of slowly beating sawtooth waves with a touch of vibrato, topped off with a resonant filter sweep sounds wonderful.

Next month

We now have a system that plays notes with an arbitrary 'bum note' in between, unless the VCO muting circuit (Fig.35, Part 2) is employed. Next month, we'll add a sample-and-hold circuit, VCA, VCF and envelope generators to make a synthesiser that can be easily played.

Keyboard and circuit PCBs

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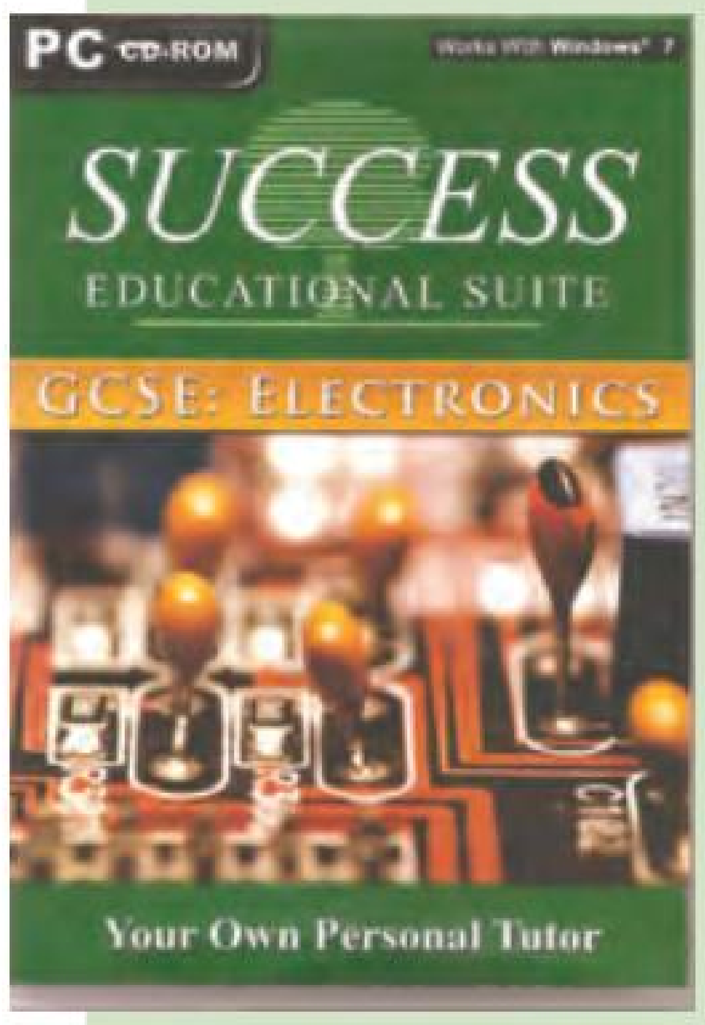

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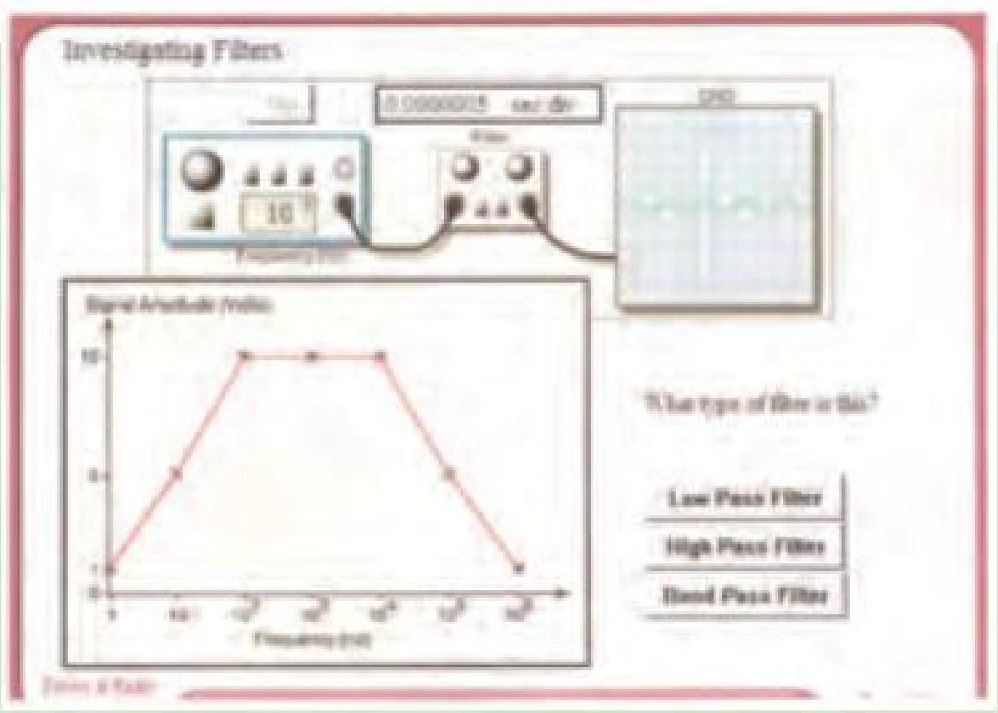

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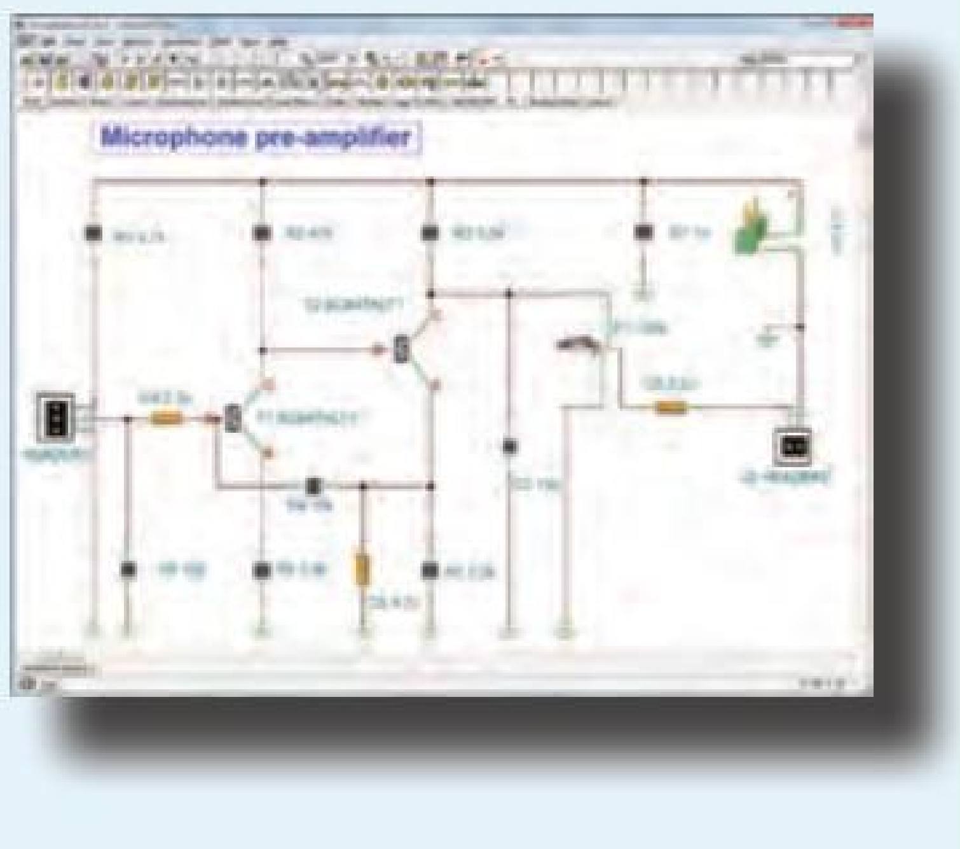

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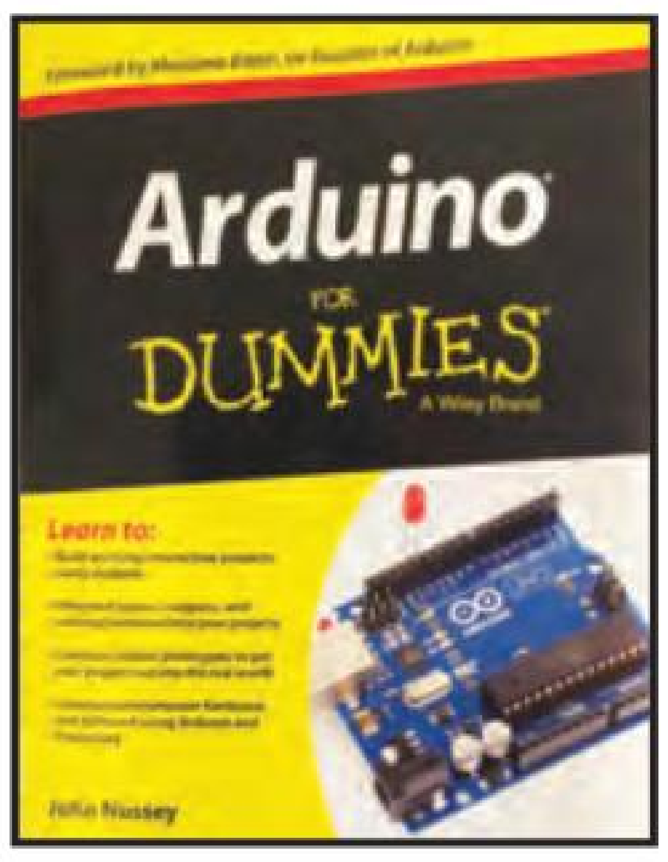

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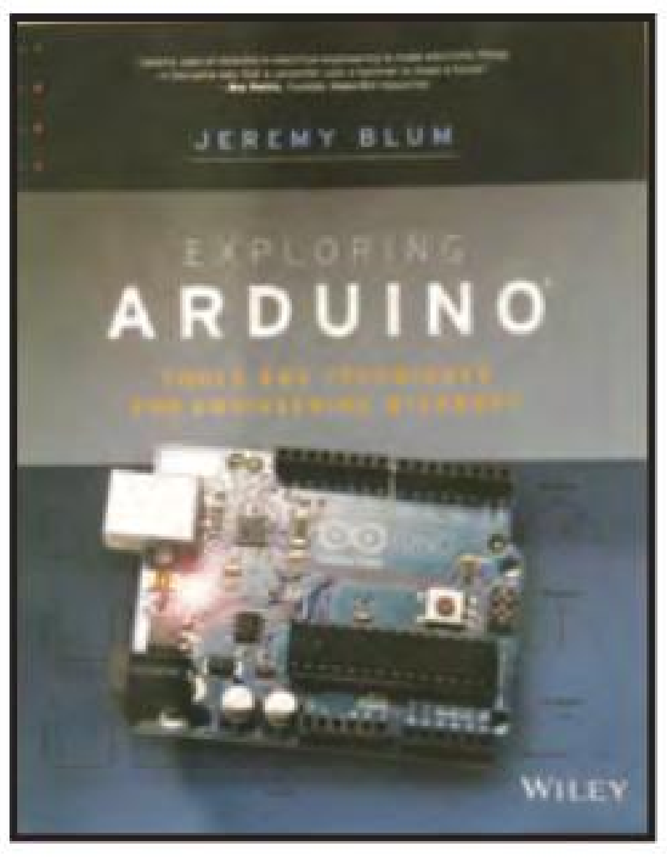

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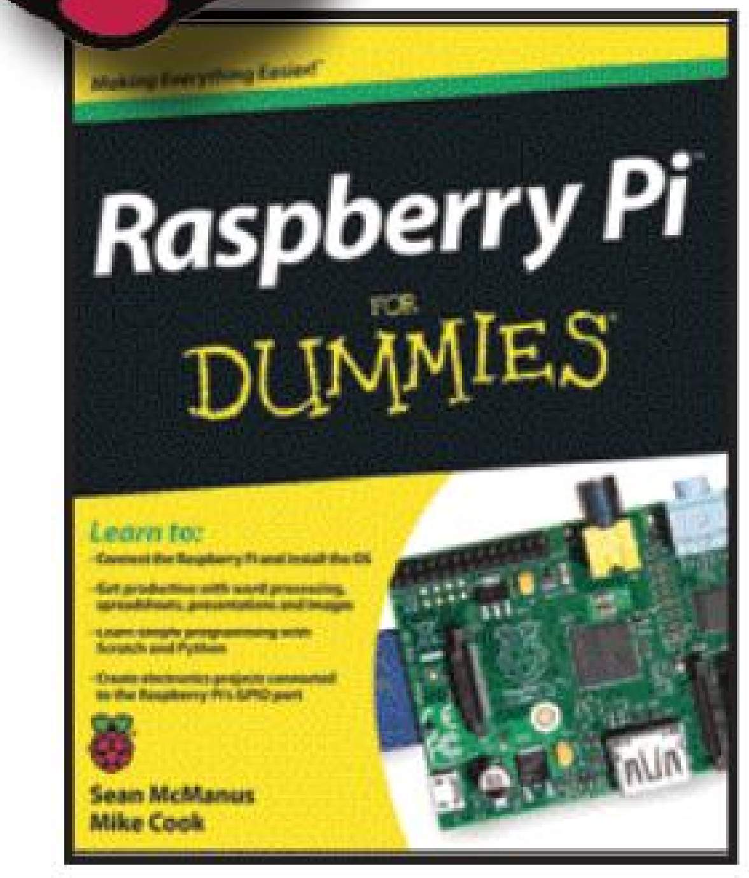
RASPBERRY PI



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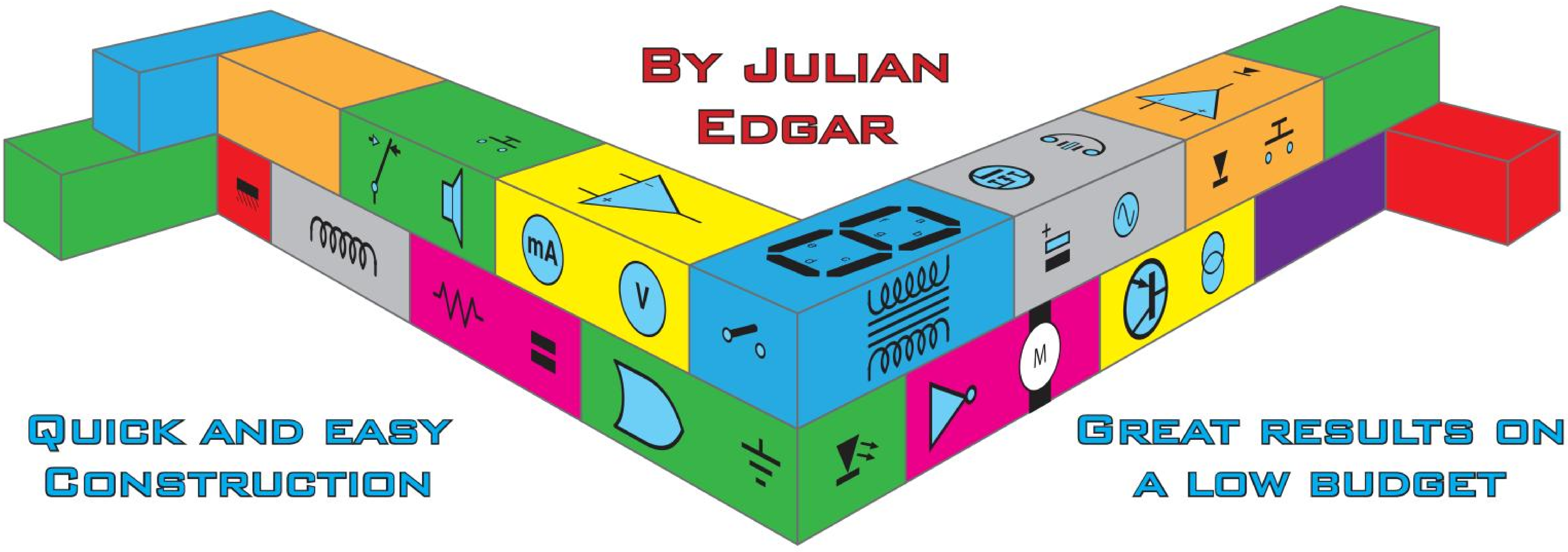


By Julian Edgar

Quick and easy Construction

Great results on a low budget

Mini Hydro Power Station!

Large complex projects are fun, but they take time and can be expensive. Sometimes you just want a quick result at low cost. That's where this series of *Electronic Building Blocks* fits in. We use 'cheap as chips' components bought online to get you where you want to be... FAST! They represent the best value we can find in today's electronics marketplace!

So what's that? You'd like to go off-grid and have your own power supply, preferably generated by renewable energy? Well, the device shown here won't actually do that – but it's well made and a lot of fun! It is also a great demonstration of the power of water under pressure. Available on **www.banggood.com** under product ID 961555, the '3.5W 8.8-15V DC Hydroelectric Power Micro-hydro Generator' will cost you under £6.50 delivered to your letterbox.

Plumbing and pressure

With a size of about 80mm (across the hose connections) by 80mm length and 40mm across the round body, the hydroelectric generator assembly is quite compact. Hose connections are by standard half-inch plumbing fittings. Depending on the water source that you're connecting it to, you might want to use a fitting that runs to a hose, or screw it straight onto a water pipe outlet. Either way, you'll probably need to visit your local plumbing supplies shop for some cheap plastic fittings.

Don't try to feed the generator water pressure achieved just by gravity – unless you have a lot of head, it won't work. Minimum supply pressure is listed as 0.08mPa (about 12PSI) and maximum is 0.45mPa (65PSI), so it's best run from the mains water supply. Depending on the water supply pressure where you live, you'll likely need the tap turned fully on to get best results from the little generator. (Incidentally, if in fact you do wish to supply it from a tank or dam, you'd need a head of about 46 metres (150 feet) to achieve the maximum specified pressure.) The generator will cope with water temperatures of up to 85°C.

This tiny hydroelectric generator is available for under £6.50, delivered to your letterbox. It outputs DC and has a peak power of about 1.5W.

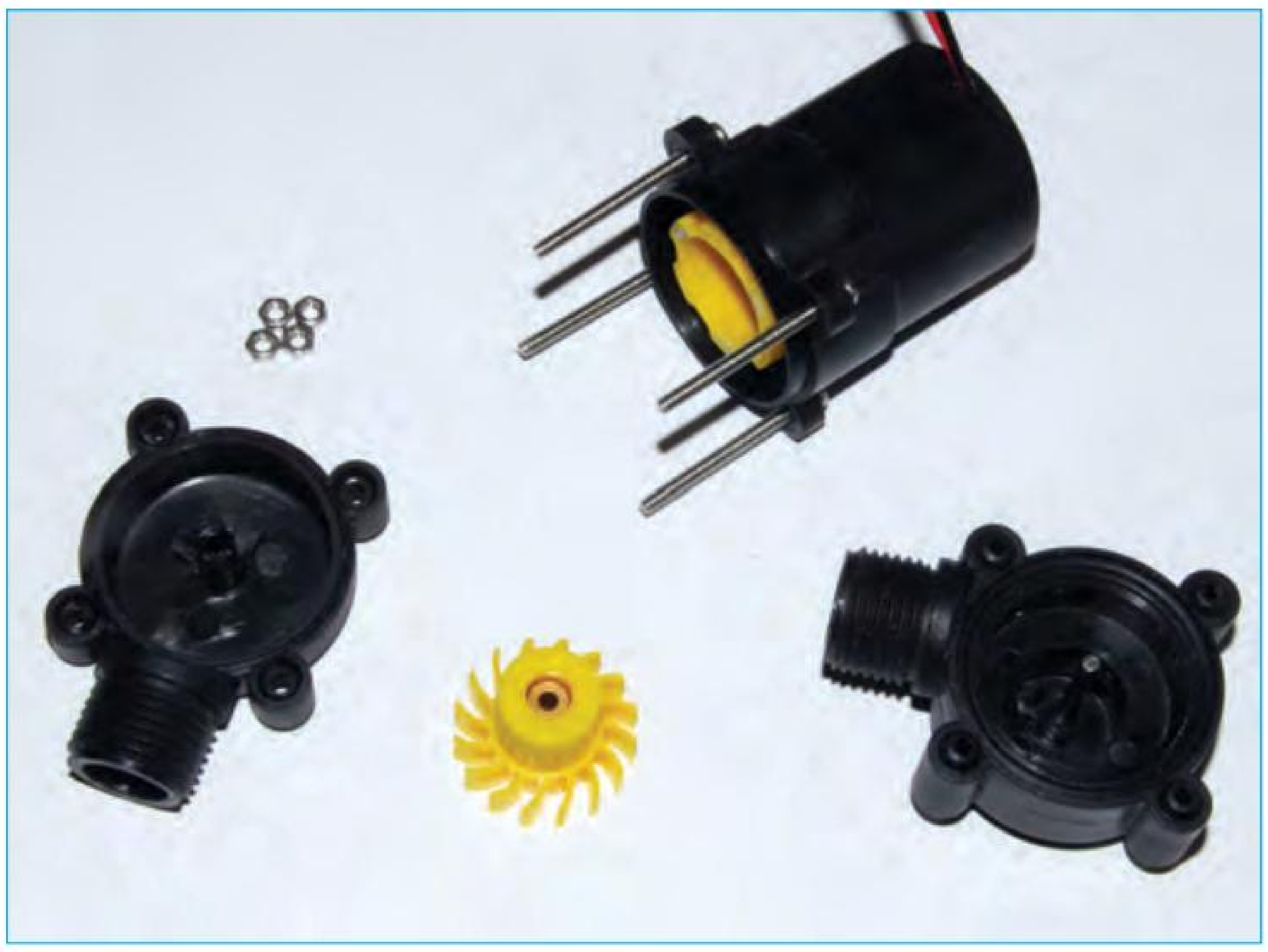
Construction

Inside, the unit is surprisingly well made. The device is separated into two areas – the generator (which I couldn't get open) and the water turbine. The turbine rotates on a brass bush and uses a stainless steel shaft. The outside screws and nuts are also made from stainless steel.

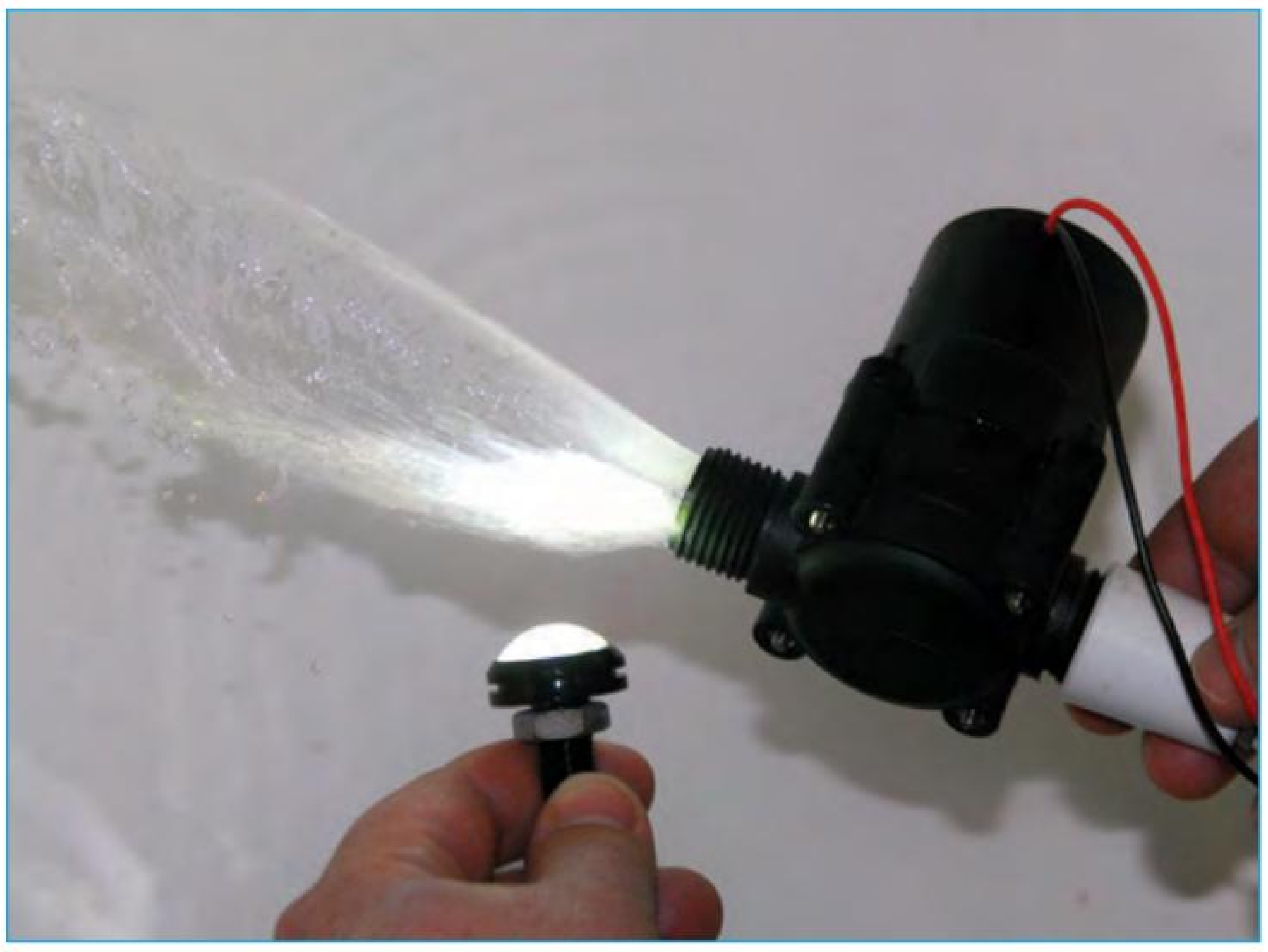
The turbine part of the design is sealed by an O-ring, and the drive to the generator is achieved magnetically, so it should be impossible for water to get into the generator. That said, the wiring connections to the generator are not sealed, and so when mounted, the device should be oriented so that the electrics are located above the water connections. That way, any leak won't enter the generator.

Operation

To operate the device, connect a hose to the inlet. The water flow direction is shown by an arrow on the base of the unit. The outlet connection can be left open, or the generator can be mounted in-line; eg, within a length of garden hose. After plumbing the generator into place, connect an electrical load to the wiring connections – the output is DC.



The unit is surprisingly well made. The water turbine uses a brass bush that rotates on a stainless steel shaft. The turbine end of the device is sealed by an O-ring, and is magnetically connected to the generator.



Using mains water supply, the hydroelectric generator is powering a 1W LED to full brightness. Note that there is still plenty of pressure on the outlet side of the turbine.

Electrical power

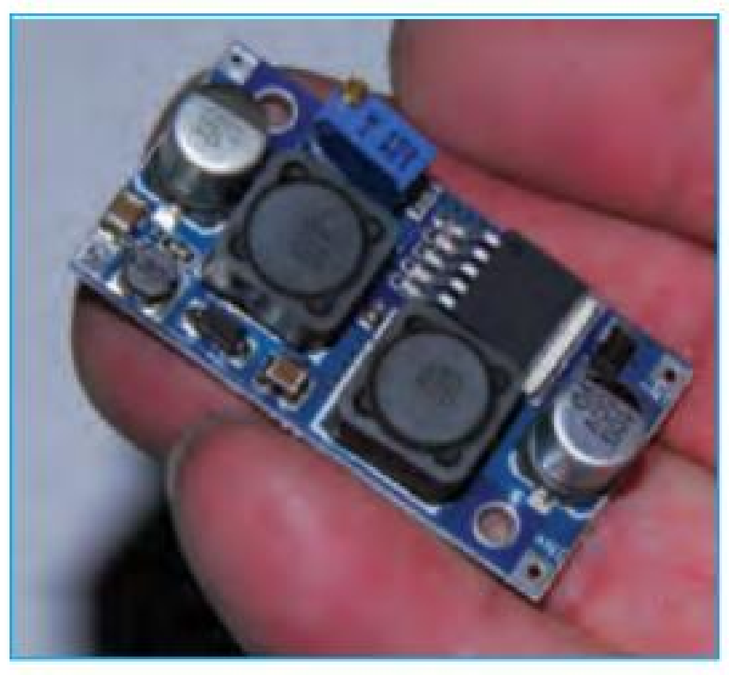
And what is the maximum power output? Something like the Hoover Dam? Well, no. In fact, I think that even the stated power of 3.5W is a bit optimistic. I measured an output of 1.5W, with 18.4V off-load dropping to 12.5V with a load drawing 120mA.

Now, once upon a time, an output of 1.5W would have meant that you could do little with the generator, but with high-efficiency LED lighting you can do a surprising amount. I chose to run a single 1W LED designed for car use (ie, suitable for12V) and it lit up superbly.

So what use could you make of the hydroelectric generator? If your partner agrees, it would make a great addition to the bath or shower – with an added high-power LED, lighting up the room whenever water is flowing. Me? Well, here in hot Australia, I love the idea of attaching it to the garden hose and shining a light wherever you are watering at night.

Of course, the hydroelectric generator is also ideal for a school science lab, or even a pre-school – with water splashing everywhere, kids will love it!

Next month



This tiny buck-boost module can output from 1.25–35V with a supply voltage anywhere from 3.8 – 32V. It boasts a realistic input current maximum of 1A.

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All prices include VAT and postage and packing. Add £2 per board for airmail outside of Europe. Remittances should be sent to **The PCB Service, Everyday Practical Electronics, Wimborne Publishing Ltd., 113 Lynwood Drive, Merley, Wimborne, Dorset BH21 1UU. Tel: 01202 880299; Fax 01202 843233; Email: orders@epemag.wimborne.co.uk. On-line Shop: www.epemag.com**. Cheques should be crossed and made payable to *Everyday Practical Electronics* **(Payment in £ sterling only)**.

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Next Month

Content may be subject to change

Super-7 AM Radio Receiver – Part 1

So why, in this day and age, would you want to build this *AM Radio Receiver* – when you can probably buy one much cheaper? Well, you'll never learn anything by buying off the shelf and you won't have the fun of constructing something that works. If you enjoy radio then this project is a must!

High-performance Dipole Loudspeaker

This loudspeaker, intended for smaller homes and apartments, will really challenge your assumptions about speaker cabinet design. In fact, it has no cabinet – and yet it is a wide-range design with a frequency response from 20Hz to 18kHz. Intrigued? All will be revealed next month!

6GHz+ Touchscreen Frequency & Period Counter – Part 2

This new *Frequency Counter* has greater bandwidth and more sensitivity than any previously published design, and its large touchscreen display makes using it a breeze. Next month, we'll describe how to assemble the two PCBs, test them, load the software and put the case together.

Banggood's $30 100kHz-1.7GHz build-it yourself SDR kit

This low-cost Software-defined Radio uses a standard DVT-B USB dongle to provide wide-range radio coverage from 100kHz to 1.7GHz. How do they manage it at such low cost? It turns out that they use a 'direct sampling' approach which eliminates some of the circuitry which would otherwise be required. So, how good is it? Find out in the November issue!

PLUS!

All your favourite regular columns from *Audio Out* and *Circuit Surgery* to *Electronic Building Blocks, PIC n' Mix* and *Net Work*.

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L=123.4µH 200kHz
Impedance 200kHz
+25.6 +j155.1Ω
Mag/Phase 200kHz
157.2Ω +80.6°

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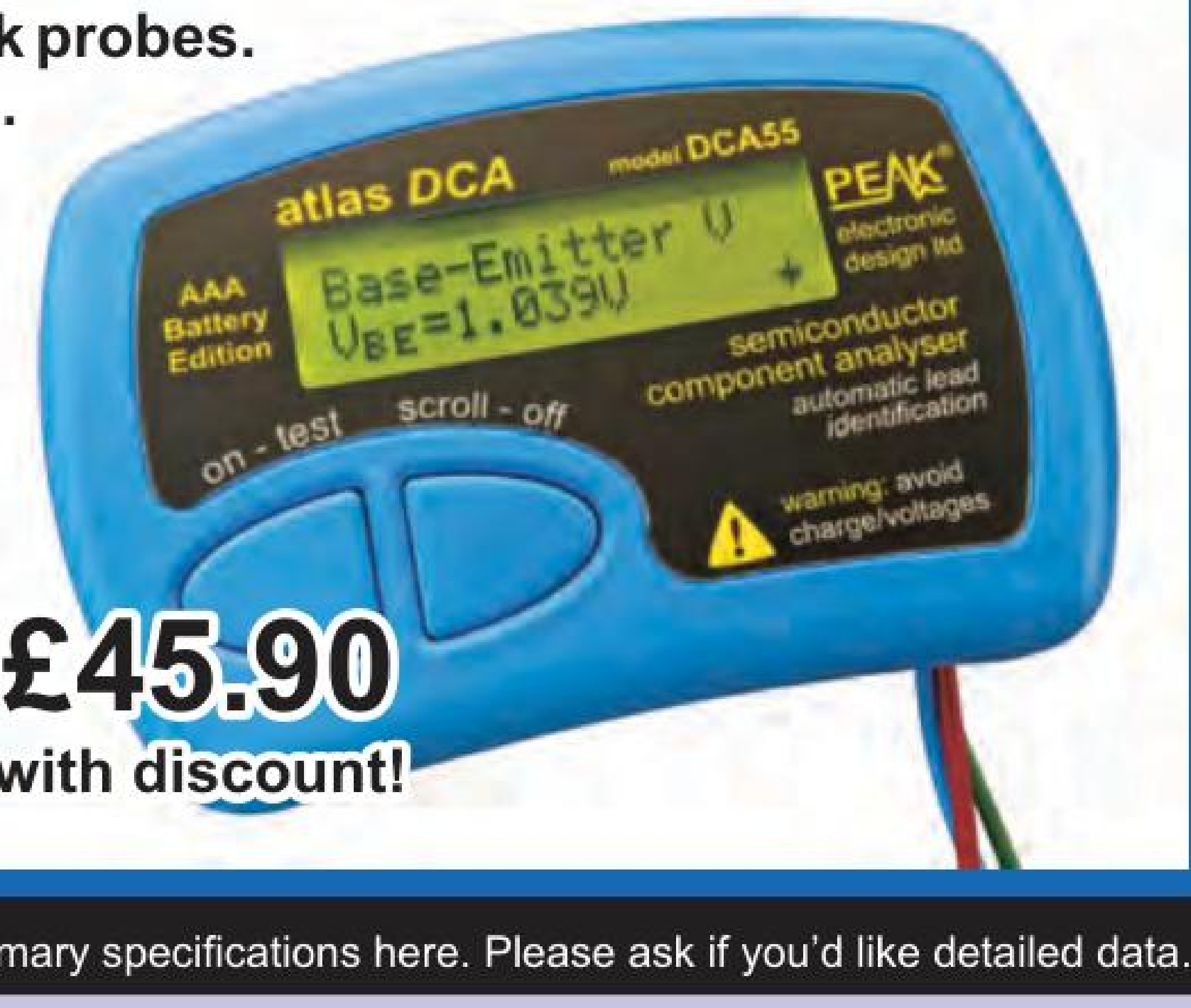
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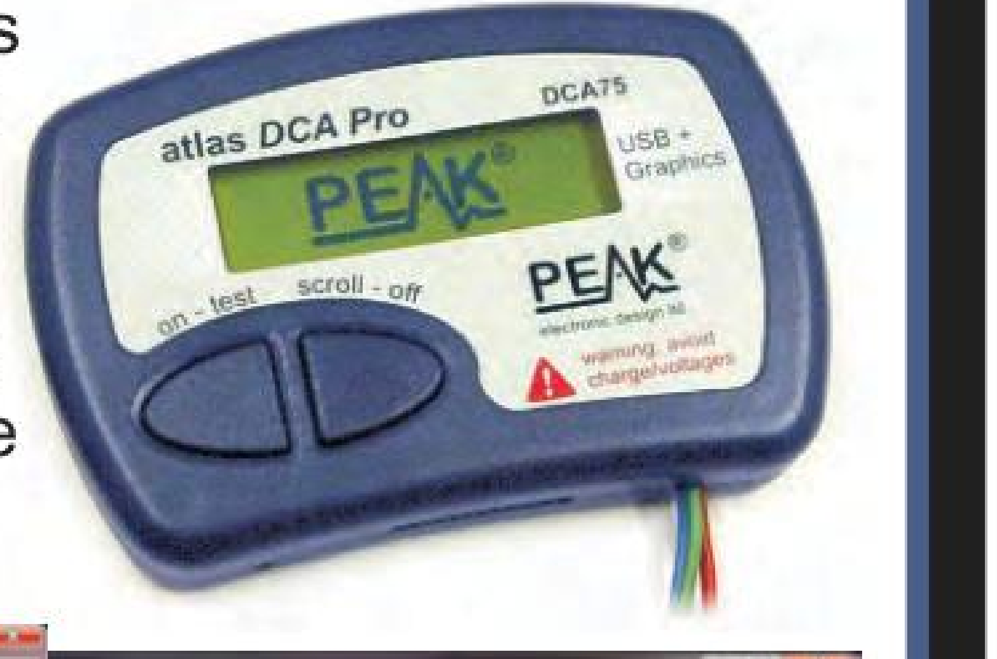
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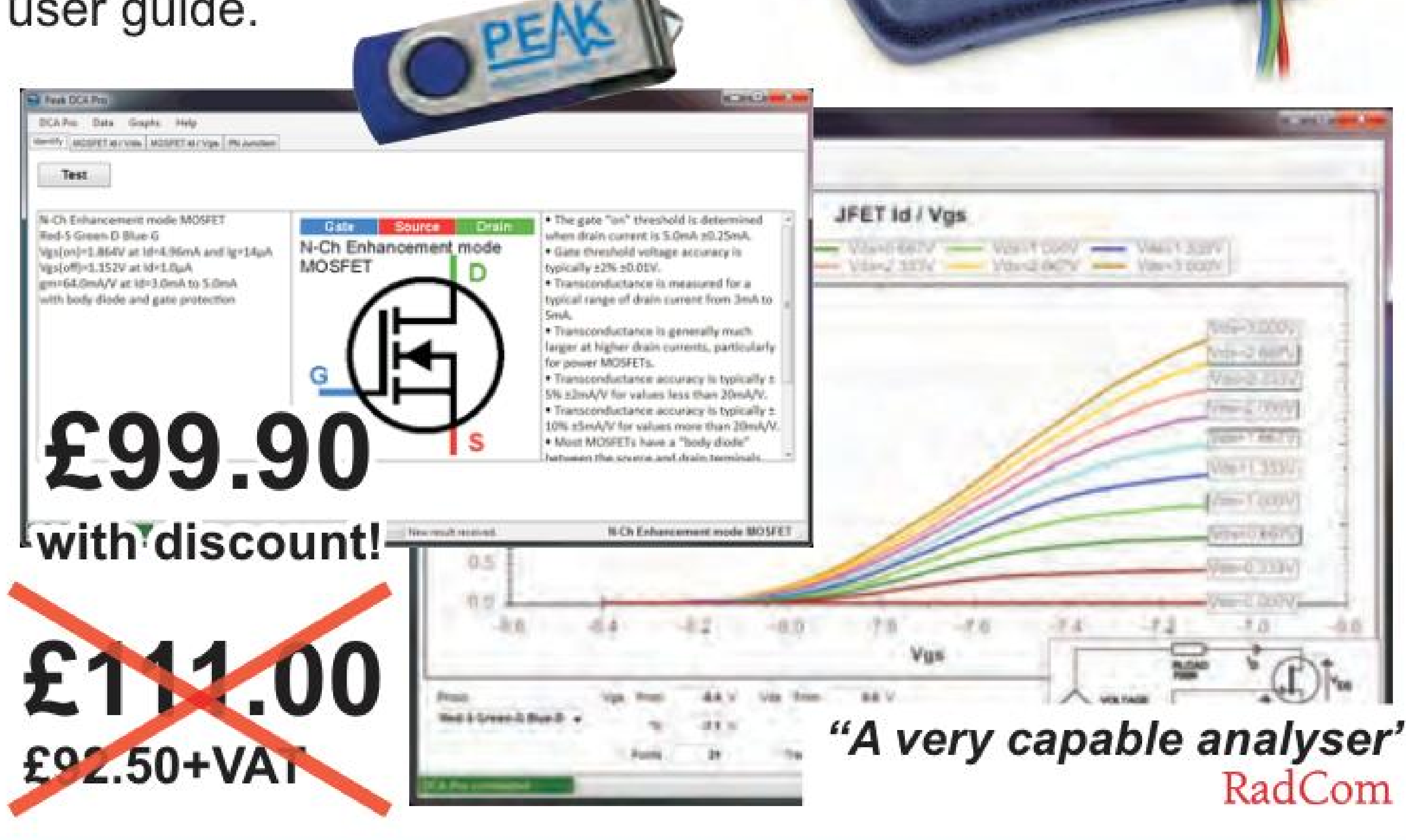
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